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Papers included are the following: aspects of mobility in the blind by J.A. Leonard; the development and analysis of tactual measures of intelligence for the adolescent and adult blind, a summary of a doctoral dissertation by Eoline Christine Cull; an investigation of human visual information transmission, a doctoral dissertation by Ronald Joseph Massa; and the vestibular system and human dynamic orientation, a paper derived from a doctoral dissertation by Jacob L. Meiry. Fifteen research suggestions and 24 publications are listed, and a research bulletin supplement describes 36 products devised for the blind. (LE)

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ADDENDUM

The work reported by R. J. Massa in this issue of the *Bulletin* was performed as a part of his doctoral dissertation at the Massachusetts Institute of Technology, and was essentially completed in June, 1961. More recent work is reported by him in "The Role of Short-Term Visual Memory in Visual Information Processing," in W. Wathen-Dunn (ed.), *Models for the Perception of Speech and Visual Form* (Cambridge: MIT Press, 1967, pp. 171-9). This research was completed in 1964. It is possible--perhaps even likely--that many of the concepts and views presented have been superseded through the results of more recent studies. Still, short-term visual memory and related sensory information processing remain interesting, important, and largely unexplained aspects of human sensory operation.

The author wishes to thank the American Foundation for the Blind and its publication staff for their interest in this manuscript and their assistance in editing and preparing it for publication.

ERRATA

On page 61 of *Bulletin* No. 15 ("Factors Associated with Intellectual Variation Among Visually Impaired Children") John Felty should have been identified as a National Defense Education Act doctoral fellow in Special Education at Michigan State University while the research was being completed.

TOWARDS A UNIFIED APPROACH TO THE MOBILITY OF BLIND PEOPLE*

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This is an attempt to clarify and consolidate contemporary ideas about mobility of the blind. In Part I, an agreed aim is stated, an appropriate attitude is suggested, and three standards for comparison are laid down. The different groups of people required to cooperate in achieving the desired aim are listed and four roles of research are specified. In Part II, a check-list of requirements and resources is introduced and amplified. Part III looks speculatively at the future.

Since this paper is addressed to those personally or profesionally connected with the problems of blindness much of the background has been assumed, but some references for general reading are provided in the bibliography. All the same it is necessary to make one point clear. Frequent reference will be made to "the blind" as an apparently homogeneous population. We all know that this is not true in many respects: blind people differ among themselves as much as sighted people but they do all share the common disability of severely impaired or completely absent vision. We also know that even on that common ground there are many variations in kind and degree: people may be born blind or become blind in later life, people differ in the amounts of residual vision, and they differ in the extent of additional impairment. But if we do want to attempt any form of systemisation, it has been found useful to concentrate on similarities

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In 1965 the Medical Research Council made a five year grant to the Department of Psychology at Nottingham University to study more generally problems of mobility of the blind. This work was headed by Dr. J. A. Leonard, who was already well known within the region through lectures and discussions at Conferences and Refresher Courses organized by the Association. Dr. Leonard developed his interest in mobility of blind people in 1962 while at the MRC Applied Psychology Research Unit at Cambridge, and was asked to evaluate Snoic Aids. In 1964 he took a study trip to the United States to learn more of Long Cane and Orientation Training.

rather than differences. It may seem paradoxical, but up to a point science can best serve the individual by seeking out the common denominators, as long as one does not forget that those whom we seek to serve ultimately are unique individuals.

Those who are concerned with welfare undoubtedly also have to use the concept of the common denominator for practical purposes. But perhaps it is the different amounts of emphasis on the needs of a particular individual which may serve as one of the distinguishing characteristics between welfare and research.

PART I: AN AGREED AIM STATED

The agreed aim: To integrate the blind population completely with the sighted implies that the blind should be able to achieve the same degree of independent mobility as that enjoyed by the sighted. In practice this means that one aims at minimising the differences between the two as far as possible.

An appropriate attitude: It is submitted that in order to achieve this aim it is essential that all those concerned should take the view that maximum mobility is an inalienable right of the blind as much as of the sighted, and not a matter of privilege. In practice this means that every blind person should be provided with every reasonable opportunity to achieve a maximum degree of independence. Facilities to acquire maximum mobility should therefore be provided as a matter of routine and not merely on demand. These facilities should embrace all the known and proved resources and they should be applied with a view towards improving mobility rather than favouring one method to the exclusion of all others. It is this attitude of mind by all concerned which is by far the most important single determining factor in achieving the agreed aim.

Standards for comparison: If one wishes to assess the level of achievement present in any field one must have some standards for comparison and establish some sort of a scale. As far as mobility is concerned such a scale is fixed at two points. At one end there is the completely homebound individual while at the other end there is the blind person who is no different from the sighted person. If one takes the bottom end of the scale as a standard for comparison, relatively low levels of observed achievement will obviously be regarded as considerable progress. If one opts for the top end, achievements at present beyond our reach would have to be observed.

It is submitted that there is an intermediate standard which has at least two useful properties: it can be reached and it can be adjusted periodically. For practical purposes it is suggested that one takes as a standard for comparison the highest degrees of mobility which can be achieved by the best existing means. That is to say, one finds out what is a present best, albeit for the best only at present, and seeks to bring the majority of the population up to that standard. As more experience and knowledge accumulate, the standard can be updated as required so that there is no inherent danger of the process becoming stationary until the aim is achieved.

Required cooperation: In order to achieve the intermediate and final aims the cooperation of all concerned is required: the blind themselves in the first instance, their relatives, the home teachers, voluntary organisations, schools, the sighted population, and research. It would not be appropriate for one outside most of these areas to specify the roles of others concerned, at least at this stage. The role of research can be considered under four headings:

1. To assess the present state and level of blind mobility in the country;

2. To examine objectively and without prejudice all and any existing methods; to compare the degree of success attained by such methods having due regard to the fact that some methods may benefit one group of people more than others, and that the use of any single method need not exclude the use of others in combination;

3. To disseminate information to all concerned--that is, those listed above;

4. To extend the degree of mobility until the final aim is achieved.

This may be a tall order, and indeed it is when one considers the resources available. For quite apart from a great deal of observation of blind people moving through traffic of all kinds, research has to be directed towards fundamental issues and the development of methodology. It is therefore not at all surprising that whenever others are prepared to take on some of the many tasks planned for research those concerned welcome this shedding of the load. Always provided that there can be some measure of sharing of activities and results.

Having said this, it is important to realise the contemporary nature of research techniques and the means available to assess achievements. The crux of the matter is that one aims at measuring performance as well as assessing opinions. It is one thing to know that a certain method can be shown to achieve specified results by a group of people--it is quite another to find acceptance for a new method. It is very important to have people's opinions, but they can be very misleading in giving enthusiastic approval as well as in registering complete rejection. The ultimate test of any new method is clearly the extent to which it gains acceptance among a group of people, but there are many routes towards ultimate acceptance and rejection.

Realisation of this is perhaps more important with respect to the response to innovations by the blind than to many other groups of people. Take the case of the long cane as a recent example. A sighted observer could form an opinion about the long cane by observing those already trained and comparing their performance with that achievable by other blind travellers. The only way in which a blind person could form an opinion directly was by having some experience of it, and the only way in which it is possible to have useful experience of the long cane is to be trained by an experienced instructor. It is good to know that there are now a number of blind people in this country who have had this experience, and even better that there is every likelihood of their number being increased presently.

PART II: THE REQUIREMENTS AND RESOURCES FOR MOBILITY

It is a cardinal principle of all forms of rehabilitation or training for disabled people that one should utilise the remaining abilities of each person concerned to the fullest extent possible. I fully agree with this principle which carries the implication that any aids to reduce the disability should be as simple and direct as possible, and that only as a last resort should one go for solutions of higher levels of complexity. Having said this I want to add the following qualifications:

Although a disabled person may be able to carry out a particular function, such as obstacle detection, with one of the remaining senses and should be encouraged to do so, there is no reason why he should not also be provided with an additional means. For up to a point the more one can learn about the environment from different sources of information, the better, if only because one of the sources may have limited usefulness only: for example, many people with relatively high degrees of residual vision can only make use of this under suitable conditions of illumination, become functionally blind when these conditions are not met, and could benefit from training "as if" totally blind to cope with those situations.

Secondly, there are situations which cannot be dealt with by the remaining senses however well these are developed or trained: it is practically impossible for a totally blind person to obtain adequate and timely warning of obstacles at the level below the knees by his remaining senses alone. Without some additional aid it is virtually impossible for such a person to move in acceptable safety and at reasonable speed through traffic, however familiar the route.

The following table (Table 1) was constructed to enable one to grasp at a glance how present needs in mobility are met by existing resources. This kind of checklist is used a great deal these days by those concerned with the design of systems

Table 1

Resources

					AIDS							
Requirements	*Person (i)*				*Proved (ii)*				*Experimental (iii)*			
(a) Attitude Motivation Standards Body Schema Sense of Space	Memory	Res.Vision	Touch	Hearing	Short Cane	Long Cane	Dog Guide	Human Guide	Narrow Beam	Radio Compass	Watch	Map
(b)												
Perception												
Near		+	+	+	+	+	+	+	+			
Distant		+	–	+	–	–	+	+	+			
(c)												
Obstacle Detection												
Head		+	+?	+	–	–	+	+	?			
Body		+	+?	+	+	+	+	+	+			
Feet		+	+?	–	–	+	+	+	+			
Street Crossing	–	+	–	+	–	–	+	+	–	–	–	–
(d)												
Navigation												
Routes	+	–	–	–	–	–	+	+	–	–	–	+
Landmarks		+	+	+	+	+	+	+	+	–	–	–
Slope		+	+	–	–	–	?	+	–			
Veer		+	?	?	–	–	?	+	+	+		
Curvature		+	?	–	–	–	?	+	?	+		–
Texture		+	+	?	?	?	?	+	?	–	–	–
Time	–	–	–	–	–	–	–	–	–	–	+	–
Distance	–	–	–	–	–	–	–	–	–	–	–	+
Speed												
S		+	+	+	+	+	+	+	+			
M		+	–	?	?	+	+	+	–			
F		+	–	?	–	+	+	+	–			

of many kinds. It is based on the notion that it is possible to specify the requirements of a situation in some detail and to allocate functions to the resources available. It is used either to discuss classes of systems--which is the way I am using it here--or else for individual instances. You could copy out this Table and apply it to any of the cases in your care to establish what they can and cannot be expected to do. Taken together with the rating scale in Appendix B such a procedure may enable you to pinpoint more readily the source of difficulties experienced. I offer such a suggestion with a great deal of humility and diffidence, for I am well aware that checklists of this kind may not be of much help to those with experience of blind people who may have learned to recognise individual difficulties much more easily than an outsider like myself. Moreover, such a checklist cannot pretend to cope with all contingencies, certainly not at this early stage of development. Nevertheless, it may be helpful to be able to tick off the more obvious sources of trouble before establishing more subtle causes of malfunction.

Before discussing the contents of Table 1 it seems essential to stress two points:

1. This Table deals with the present situation and not with any future solutions. Ultimately no doubt science will eliminate blindness by a two-fold attack: preventative medicine will go a long way towards eliminating the causes of blindness and "spare part surgery" may present us with functioning artificial sense-organs, nerve-fibres, and relevant bits of central nervous structure. Both these achievements are a good way off, but not so far that those interested can afford to keep their eyes off the ball: however, as far as the present state of the art of spare part surgery is concerned it is as well to realise that one is only just beginning to be able to "replace" organs of the body which are largely under involuntary control, relatively simple in the modes of operation and, most important, where the basic principles of operation are reasonably well understood.

2. Inevitably at present there is a need for formal and extensive training for mobility. Indeed, on the basis of the present evidence, it is only reasonable to assume that even when functioning artificial eyes can be produced there would be a longish period of "learning to see" at least for the congenitally blind. I know well that there is a great reluctance among all of us to have to undergo long terms of training for any task. One wants to be sure that the effort required will somehow be commensurate with the achievement to be obtained. At present many blind people are less bothered by slow and stumbling progress than by the prospect of having to spend four weeks of intensive mobility training. This is a fact of life which you have to deal with to a greater extent than I, for in the last resort my task is primarily to demonstrate with those who are willing what can

be achieved. But I am willing to bet that those of you who have seen efficient guide dog travel or who will be seeing efficient Long Cane travel will have a standard to set before those in your care which they may well find worth spending some time in acquiring.

Requirements

Down one side of the Table are listed a number of requirements in four large groups: the first are general requirements, the second deals with perception, the third with obstacle detection, and the fourth with navigation.

(a) Attitude, standards, and motivation are obviously the most basic requirements. I wholeheartedly agree with those who maintain that a person has to be motivated to become mobile. But I would add that the knowledge of what can be achieved by most people will in itself provide a certain amount of that motivation. Once blind people can be made to accept that bumbling and stumbling need not be inevitable concomitants of independent mobility their attitude may be changed as much as those of older people who used to accept a degree of blindness as an inevitable concomitant of old age.

A sense of the position of one's body in space, and of one's limbs in relation to one's body is likely to be an important precondition to good mobility on theoretical grounds. Thus people with additional handicaps affecting this experience might find it hard to become fully mobile. But we know very little about this as yet.

(b) We divide perception into two classes: *near perception* deals with everything which is sensed directly by the body surface, for all practical purposes this means the senses of touch and pressure. *Distant perception* is served by vision, hearing and smell, that is, the senses which enable us to perceive objects without having to come in contact with them.

(c) Obstacle detection: it is useful to consider the three zones which have to be protected: head, body, and feet, as long as one does not draw the dividing lines too sharply.

I have put "street crossing" under obstacle avoidance because the crossing of streets is at present the single largest remaining class of obstacles. It is difficult enough for the sighted to cope with the rising traffic, for the blind there are two identifiable sources of difficulty:

1. The blind traveller unguided cannot deal with the two opposing streams of traffic separately by clearing near traffic first, waiting in the middle of the road, and clearing distant traffic next: if he ventures forth at all, the crossing has to be carried out in one fell swoop. This may mean that one-way streets are easier to deal with by blind travellers since they only have to take account of traffic coming from one direction. Were it not for the fact that one-way streets tend to have

higher average traffic speeds one might consider them as preferable for blind crossing. We hope to find out more about this.

2. The blind traveller does not have any opportunity of communicating with drivers of cars by "eye contact" as does the sighted pedestrian. It is perhaps not realised how much the sighted "talk to each other only with their eyes" on these occasions, and the facilitation which this provides.

(d) Navigation: basically we are talking here of routes, landmarks, judgments of time and of distance. By the requirement "routes" is meant some form of memorised pattern, description, map, etc., of a complete route or set of routes. "Landmarks" refers to the need to handle a wide range of landmarks, for example, the end of blocks, pillarboxes, smells, noises, etc. Because we are beginning to get to know something about them in detail I have listed four classes which appear to be particularly useful: slope, veer, curvature, and texture.

Speed here refers to either detection or speed of movement in as much as these are interdependent. You will not find many references to a speed requirement in the relevant literature until quite recently. The explicit requirement that blind travel should be at speeds comparable to that of the sighted marks the biggest break with the traditional approach to blind travel because it draws attention to the slowness of most blind persons' progress. Purely arbitrarily I am proposing here three speed categories: slow = 1 mph, medium = 2 mph, and fast = anything better than that. It is reasonable to assume that ordinary pedestrian traffic is about between 2 and 3 mph. Entries along these rows refer to the possibility of travelling safely at these speeds.

Resources

Along the top of the Table are listed the resources available. They can be considered under two broad headings: resources provided as it were, from within the individual, and those provided by the utilisation of aids of various kinds.

The first group is, again, very general: a sound mind and body are useful resources to bring to the task.

Person (i)

Memory: The psychologist considers this often separately for short-term and long-term use and tests for either exist. Just how useful they are in relation to our present problem remains to be seen.

Residual vision: This covers the range from anything better than no perception of light to the upper limit of registration for blindness. The argument ranges largely about the uses to be made of residual vision: should one encourage or discourage its use, should one allow people to find their own way of making good use of it, should one try to teach methods of utilising residual vision most adequately in relation to other resources? One of the main points to remember is that the usefulness of residual vision is often severely limited by conditions of illumination and other factors. Another point to bear in mind here, as with any of the other resources, is the possibility of allowing them to complement or assist each other: a blind person with very restricted field vision in one eye can be taught to use this for forward vision--that is, obstacle detection and steering, while using a cane to ensure safety at foot level.

Touch: Strictly speaking this includes all the so-called near-receptors--that is, pressure and joint senses. They are considered to be the most elementary of our senses. They do not allow one to receive a great variety of shades of stimulation compared with the eye, and they adapt very rapidly to stimulation--that is, they very rapidly cease to signal messages to the brain in the presence of continued stimulation; hence one does not feel the pressure of one's clothes for any length of time after putting them on. These senses are therefore poor "pattern" receptors as far as conscious perception is concerned while at the level below consciousness it is these senses which tell us continuously and pretty accurately about the position of our limbs in relation to the rest of the body, and so on.

Perhaps a good point to remember is that it is much harder to deceive the sense of touch than the other senses, and that we tend to use it to resolve perceptual conflicts produced by the other senses.

Hearing: This sense, like touch, is predominantly used to take in information of a sequential kind rather than simultaneously presented patterns: the main characteristic of speech is just this sequential character. The ear and the parts of the brain associated with it, have evidently been developed to a fine point to deal with just this kind of task. We can convey a great deal of information through hearing provided it is of a speechlike nature and utilises the sequential basis of the mechanisms provided. Hearing, being served by two sense-organs placed on either side of the head, does allow us to perceive "in depth," to make judgments of distance, direction of sound sources, and the nature of their movement in relation to ourselves or other sound sources. Within limits our auditory mechanism can deal with some of the information needed for a crude form of echolocation and it is pretty certain that this is how "facial vision" is brought about. But in general all the sorts of discriminations required for adequate spatial orientation are badly served in the auditory system of humans as compared with other animals. On the other hand, what there is can be used to good effect, and can be trained to become better. In practice it is well worth noting that however good a blind person's "facial vision," he will move past obstacles by giving them a considerably wider berth than is strictly speaking necessary.

Hearing, then, is obviously one of the most important resources available to the blind person; without it life becomes markedly and drastically more difficult. Hence it is important to ensure that a blind person's hearing is kept in a good state of repair basically, augmented by suitable hearing aids if necessary (binaural where necessary), and that methods of training for better hearing are studied and made known.

In summing up on the senses it is important to realise that one has to think of them in relation to the parts of the brain to which they feed information and to the whole brain structure in turn. In man the visual system predominates over all others, in bats it is the auditory system which almost crowds out everything else in a small but very effective brain box. Hence, even though we may feed man with the same sort of information as is used by a bat, it is unlikely that he will ever be able to achieve a bat's feats of echolocation. The senses which remain to a blind person in the complete or partial absence of vision are his first and most immediate resources. They should be taken great care of for with man's most important information gathering system out of action their role becomes vastly more important.

The section above has dealt with the utilisation of the remaining senses. The next class of resources are those which make the blind person rely on existing aids to a greater or lesser extent: canes, guiding by dogs or by humans.

Proved Aids (ii)

Short cane: Starting with an ordinary walking stick painted white and progressing to the currently used elegant collapsible metal cane, this aid has been with us for some forty years. Apart from its usefulness in extending the physical range of the hand, it serves as a signal to other road users, to draw attention to the fact that there is a blind person. We all know that it is this second feature which has two sides to it: those of us who for reasons of welfare or skill acquisition wish to see the blind equipped with this aid realise the tremendous value of the "signal," for it enables the sighted to offer assistance in those situations in which the blind person cannot operate without sighted help, for example, the crossing of busy streets. To many of the blind one suspects that the white cane is still more of a necessary evil than a good friend; for a variety of reasons it is a negative status symbol. (A guide dog on the other hand, which is not exactly inconspicuous, appears to be a positive status symbol.) There is much that can be done with the short cane and its efficient use can be taught. At the RNIB's rehabilitation centres for instance, this now forms a major part of mobility training.

Long cane: This is the aid forming the core around which the Hoover technique was built. It is an aluminium cane with a hard fibre tip reaching to the tip of the user's elbow, or the bottom of the sternum, which makes it some four to six inches longer than a walking stick. A walking stick is intended to bear your weight at the moment you change from one foot to the other so that it acts as a sort of pivot touching the ground straight in line with your body. The long cane is designed to touch the ground just one step ahead of your body, sensing the area in which you are about to set your foot. It is this which enables the long cane traveller to walk with more assurance and grace but the extra length of the cane makes it necessary to adopt and acquire an appropriate technique. The best description of this by a British user has appeared in the *St. Dunstan's Review* for April, 1966, by Walter Thornton. The crux of the training is the need to incorporate the cane into the body schema, to make it as much a part of you as your pen, your bicycle, or your car--all tools which you can use efficiently and safely without having to think about their operation continuously. I have every reason to believe that the long cane and its associated training programme constitute the largest advance in independent mobility technique in the last two or three decades, for it should enable those who can be trained to move about in considerable safety. And it looks quite possible that those who can be trained comprise a wide section of the blind population.

Dog guide: Readers here will know most of the relevant facts about guide dogs. There are a number of papers to which they can refer if in any doubt, particularly the information booklets published by the Guide Dog Association. Here I only wish to stress the following points of interest:

1. The special nature of the necessarily intimate relationship between the blind person and the dog. The owner has to be able to rely on the dog completely while the dog is in harness, but the dog also has to be able to rely on the owner to retain complete control. Both are living creatures who have been trained singly and together to carry out a special task. It is in the nature of such training that it has to be "tuned up" periodically, and that both partners have to prevent themselves from becoming distracted during work. Hence, in every sense of the word this is very much a working relationship. It is also almost inevitably an emotional one.

2. The question of independence. Evidently while the blind person is working with the dog they are dependent on each other. But a blind person with a dog is of course much less dependent on sighted help, he can cross roads with a great measure of safety for instance. The main problem tends to arise once the blind person is not using his dog for some reason or another. There is absolutely no reason why guide dog owners

should not be trained in other forms of basic mobility techniques as well, as long as this does not interfere with their efficient cooperation with the dog.

3. The two points mentioned may well go some way towards accounting for those blind persons who, although they do not want to take up training, are eligible for guide dog training on the grounds of minimal vision, age, general fitness, and intelligence: there are clearly people who cannot enter into the appropriate relationship with a dog (or with another person for that matter) and there are people who feel that their independence is threatened by working with a dog. On top of this there are real or imagined limitations imposed by the blind person's occupation. To the extent that the guide dog does appear to be eminently useful, the restrictions imposed on its wider applicability are clearly a subject for research.

Human guide: The oldest and steadiest of resources, usually completely untrained and only mentioned as an afterthought by writers on the topic of blind mobility. As far as I know there is as yet no programme for training the relatives of blind persons either generally or specifically--that is, either for their role in rehabilitation as such or in mobility. On the other hand there is only a little training given to blind persons concerning their relationship with the sighted. We know the problems and we know some of the techniques that can be taught: for example, the human guide, particularly when a member of the family, tends to be over-protective (and quite naturally so); and there is a right method for guiding a blind person. There is the other problem of obtaining sighted help when required as well as detaching oneself from it when it is no longer required. Provision for training of the human guide is clearly indicated in future training schemes. All I have said here about the human guide refers to formal programmes. Home Teachers have, of course, coped with these problems effectively for many years and we should be able to benefit from their accumulated experience in this as in other fields.

This, then, concludes the part dealing with resources generally available and we now turn to the last group, those in various phases of experimental development.

Experimental Aids (iii)

Narrow beam ultrasonic aid: This is essentially a small, portable form of sonar with an auditory output to the blind person. It provides, over a range of some 20 feet, the very rough equivalent of a very narrow tunnel vision. It emits a signal and when this strikes an object an echo is returned. The properties of this echo carry a great deal of information about the distance and nature of the object. By adopting an appropriate scanning pattern and putting together the information gathered successfully it is possible to build up a fairly detailed "picture" of the environment from the information produced by the aid. The problem arises when aid and information have to be handled by a human being who cannot see. I have gone into some detail over this at a Southern Regional Association Conference (S.R.A.B. Conference Report No. 53 Ed.), and nothing which has happened so far has made me change my basic point of view on the matter: there is a place for such a device in our armoury since it is the only device which can help the blind person to perceive at a distance in some detail. To the extent that such distance perception can be learned and utilised it is clearly desirable. At present my guess is that the device will be found to help as a navigational aid to assist in straight line travel (by obtaining a fix on a known landmark such as a beacon the other side of a crossing), and in the recognition of certain landmarks at a distance.

There are extensive evaluations of the device being carried out at present all over the world. The results of these evaluations will be presented to an international conference early this summer.

Other electronic aids have not reached the production line as yet. Of these, the most interesting is one which, designed by Mr. Lindsay Russell, emits a broad beam ensuring coverage for the whole of the upper part of the body, and displaying simple information about the presence or absence of obstacles in four zones of increasing proximity to the body. This device therefore should enable the blind person to know the extent to which the forward path is clear, leaving the finer detail to other resources.

The great attractiveness of electronic aids to the blind is their lack of conspicuousness and/or their having a positive status symbol. To the more theoretically minded their attractiveness lies in the possibility of providing early warning and a very partial substitute for distance receptors. The drawback lies in the simple fact that the information processing is eminently complex and does not utilise as direct a system as do other aids.

Radio-compass: In the absence of vision it is difficult to maintain a straight course, and even more difficult to notice when one has departed from a straight course. Apart from this there are a set of occasions where it is useful to have available a constant reference direction when moving through unfamiliar territory (the sighted have the sun, or a distant dominant landmark like a hill or a tower for this). Active work has been going on to provide the blind with a suitable aid. So far it appears that the only viable device is Swail's radio compass which relies on the directionality of the ferrite core aerial inside an ordinary transistor radio. By tuning to a known station it is possible to direct the set so that one obtains maximum signal strength, and this in turn can be suitably displayed to a blind person to provide a "Null" signal. There are still many problems to be solved, but a first step has been taken by the Sensory Aids Evaluation and Development

Center under John Dupress in taking the set out of the hand and strapping it to the chest, thus cutting out one considerable source of error due to variable hand-positions.

In whatever form it will eventually see the light of day, there is undoubtedly a need for a simple and reliable straight-line indicator for all kinds of blind travellers.

Maps: The idea of providing blind persons with simple, portable maps is relatively new. I have written about this in the February issue of the *New Beacon*, and we are continuing to work on this. Whether we are going to plumb for verbal or spatial maps one thing is already quite clear: there is a need for the development of a common language to describe commonly experienced mobility situations, so that at the very simplest level blind people can describe routes to each other and can understand the descriptions given by the sighted. To the extent that existing systems already make use of such languages one would hope that they can be embodied. For example, the guide dog people do have a set of terms with which to describe and specify some aspects of mobility, and these terms do already have some common currency.

The point about maps, the technicalities apart, is that they are yet another means of enabling the blind person to be more independent, for they should enable blind persons to choose their own routes, and to pursue them without the intervention of the sighted, or with minimal intervention.

This, then, completes the resources section, ranging from remaining senses through existing systems, to various more or less experimental aspects. The next step is to look at our Table to see how requirements and resources are matched.

Using the table: One can start using the Table either by going along any given row, or by going along any given column. There is no need to go through every item here. Instead I shall pick a few examples.

If we take the row marked Perception, Distant, we can see that this is served by residual vision (if this is present at an adequate level), to some extent by hearing, by a guide dog, a human guide, and by a narrow beam aid. It is not served by touch, or either of the canes. Thus a totally blind person has only got hearing to obtain some distant perception. If we want to provide him with additional resources we have to look to a dog, a human, or a narrow beam device. If for some reason he is not suitable for guide dog working, there is only the human or the narrow beam.

Take the row marked Obstacles Detection, Feet. This can be achieved by residual vision, by touch if one walks slowly enough or is prepared to accept the odd injury, by a long cane, dog, human, and narrow beam marginally only: it has to point in the right direction and any drop of the terrain is hard to discriminate in sufficient time to stop oneself even at moderate speed. At foot level, neither hearing nor a short cane are of much use when walking even moderately slowly. If there is no residual vision there is really nothing among the remaining senses that can assure the blind traveller of safe progress with regard to obstacles at foot level if he wants to walk at any reasonable speed. He does need some form of aid: the long cane, dog or human guide. For those who do not want a dog or human guide, safe travel in this respect can be obtained only by use of a long cane.

Another example, Routes: as defined earlier, routes as such have to be either memorised or put on a map. This also applies to the guides. Unless we have got maps the blind traveller has to rely on memory or a guide.

Let us look at it the other way round and take the column headed Long Cane: it is of no use for distant perception, for obstacle detection at head level, for routes, for the detection of slope, distance travelled, or time elapsed. But it is eminently useful for obstacles at body and foot level, for all speeds of travel if one can deal with obstacles at head level by hearing, for the detection of curvature--possibly also for veer and landmarks.

It will already have become obvious from these examples that one gets most out of using such a Table by looking at the configuration of yesses and noes, by taking various rows and columns in combination. This works in two ways: on the one hand one says for instance, given no residual vision and the requirement to move at the same speed as other pedestrians, what is the minimum needed by way of aids? On the other hand one can also find out how many requirements can be served by a multiplicity of resources. It has already been pointed out that one makes use of multiple inputs in everyday perception to facilitate the process and because there is always the chance that one input may be temporarily inactive at a critical moment: if you can hear and see a car approach you while on a crossing, a sudden loud noise from somewhere nearby does not put you out of action; if you have a long cane to sense the ground ahead of you the fact that an imminent cloudburst stops you from using your residual central vision need not stop you in your tracks.

Consider another use of the requirements resources Table: blind persons having too much residual vision are not held to be suitable for guide dog work. Thus there is always likely to be a group of blind people whose residual vision is not sufficiently great to allow them to move about entirely unaided, but too much to be considered for guide dog work. Numerically they could be about a third of the registered working population, say 10,000, and at least a similar number in the higher age-groups still sufficiently active to want to move about.

When one comes to using the requirements resources Table together with the Mobility Competence Scale in Appendix B, one does so in order to rule out certain possibilities. Say that a blind person comes under heading 12; travels in familiar environment with a cane, does not travel in unfamiliar environment.

The first thing you may want to know is whether he could be expected to move through unfamiliar environment on purely technical grounds; is his mind alert, is his hearing all right, is his cane technique suitable? Say the answer to all these is yes, you then have much better grounds for dealing with the person at the next level of complexity, for example, there may be a lack of interest or some emotional involvement. This is the same drill which doctors follow when they set about carrying out a diagnosis: if somebody complains of being tired and out of condition it helps to know whether or not he is basically physically fit.

Checklists, tables, and rating scales by themselves are nothing. They are tools which have to be used with sympathy and intelligence. But used thus, they can save time and assist the user in arriving at a helpful solution. From the point of view of the research work of course, the requirements resources Table is the essential jumping-off ground for it shows us the gaps to be filled: for instance, up to some two or three years ago the most serious problem appeared to be the obstacles at foot level, and particularly the step down, the open manhole. We now think that the long cane should be able to deal with this better than anything other than guides, human or canine. So the next big obstacle of our time is street crossing--bad enough for the sighted, perhaps not an immediate challenge for research but one to be kept in mind since it would appear to be the largest single cause for "lost time" on travel through familiar territory.

Or consider the row "Distance": it is completely blank and waiting to be filled in.

PART III: THINKING ALOUD ABOUT THE FUTURE

Once again in this section I do not want to go very far in speculations about possible advances in mobility aids for the blind, but rather to indulge in some speculations about a future which could already be in our grasp.

On the aids side, though, it is likely that we shall see an extension of the use of electronic distance receptors and straight line travel indicators and before the turn of the century we may see the first glimmer of spare part surgery in the field of blindness beyond the present state of the art.

On the side of immediate research my guess is that we are moving towards the possibilities of providing quicker and more reliable assessment of the remaining abilities of blind persons so that you will be in a better position to make recommendations for suitable courses of training. Work which has been done in various parts of the world could be combined to put blind persons through a test battery to assess their ability to deal with a range of important aspects of mobility: hearing, balancing, veering, slope detection, orientation, and so on.

Let me say again that here as in all other areas of therapy such tests are to be thought of as tools providing one part of the relevant information on the basis of which decisions have to be reached.

It is also likely that within a few years' time, we may be in a much better position to provide evidence on the basis of which different kinds of mobility training can be suggested to different people, and by then we ought to know more about the stress experienced by different people using various mobility methods in different situations.

On the side of orientation, I am confident that progress can be made towards a common language to describe routes and a common simple system to make maps. It is already within our grasp to go much further on the purely technical side by providing blind people continuously with a kind of grid-reference of their current position, but this is the sort of solution which may be far too complex in relation to the possible need. Nevertheless, it is useful to know that there is a solution in principle.

But there are possibilities of quite a different nature which you may well think it is not for me to talk about at all. Nevertheless, I want to do some thinking aloud about the possibility of making concrete some of the things mentioned in Part I.

If there is agreement on the basic aims, and if it is agreed that some sort of new attitude is needed would it not be possible to discuss at least the administrative implications?

A unified approach towards mobility would presumably require some degree of unification of the training and rehabilitation processes. In other words, there is surely a case for being able to examine a blind person, to assess them reasonably objectively, and to recommend one of a number of alternative courses of mobility training. These courses would presumably have to be provided at general rehabilitation centres--that is, in a wider rehabilitation setting. Again, would it not be possible to have mobility training, whatever its form, carried out systematically and progressively?

By this I mean on the one hand a continuous process as far as the congenitally blind are concerned in which each successive age can build upon the earlier knowledge and in which mobility is a fundamental concept from nursery to university if necessary. On the other hand, could there not be an orderly progression beginning as soon as feasible after the onset of blindness, being sharpened during forms of "primary" rehabilitation (for example, Torquay) and continued during vocational training (for example, Letchworth), and maintained once the blind person returns home?

Now in all this, and for many reasons, I can see the possible need for a new kind of specialist in welfare work, knowing full well the extent to which such a notion cuts across current developments. But might it not be useful to have, say, at the level of each local authority, a person whose sole responsibility would be the mobility of blind persons in that area? You think that such a person would not have enough to do even if it were possible to appoint her? This specialist would have to know enough about all existing forms of mobility to assist in initial assessment, to carry out pre-training or mobility training during domiciliary rehabilitation. This specialist would look after the blind people on return to their homes, help them to become familiar with their working routes, provide running maintenance, so to speak, on mobility technique, help in making maps, and so on. The person so trained would have to know, for instance, enough about guide dog training, to know when to call in one of their after-care officers on demand. It would also be within this person's terms of reference to facilitate cooperation between the blind and the sighted. Finally, and perhaps as important as any other, it would be up to this person to assist blind persons wishing to change from one form of mobility to another: it is a common enough experience for a blind person to be able to get about practically unaided until he gets into the early forties when the decline in sensory efficiency begins to make itself felt. Such a person might well then want to take advantage of guide dog training for instance. But the main point is that one is suggesting here to have somebody available at the local level who will have been trained in, and kept in touch with, all existing aids to mobility, training, aids, guides, and to be available at all times to assist blind persons in that sphere.

It is much too early now to consider the structure of such a service, whether it should be governmental or voluntary, or any other administrative details as long as one remains aware that if such a person is to be turned into flesh and blood he has to become part of the existing welfare structure. It seems rather more important to start a debate on the need for the kind of tasks I have outlined above to be done, and done well, at the local level.

Concluding Remarks

Let me conclude then by reiterating that in order to move towards a unified approach to blind mobility it may be helpful to think of the problems in terms of matching requirements with resources, to produce specifications for both requirements and resources, to modify these if required in the course of time, and to ensure a common final aim of the maximum possible degree of mobility by whatever means are found to be suitable for the blind person concerned.

Appendix A

Implementation of Research

Research on mobility is being carried in this country as well as abroad. Information about ongoing research is disseminated primarily by IRIS.*

As far as this country is concerned the Research Committee of the College of Teachers for the Blind acts as a clearing house for all research schemes as far as they involve blind children. RNIB and St. Dunstan's have their own programmes, of which the latter's current evaluation of the Ultra Aid sponsored by them is at present the largest exercise.

There are a number of smaller research projects on related topics at Keele University and at Newcastle, and there are always a number of enthusiastic individuals devoting much time and effort to this form of research.

Last year the Medical Research Council made a five-year grant to the Department of Psychology at Nottingham University to study more generally problems of mobility of the blind. The following sections provide a brief outline of the extent to which this project is trying to fulfil the four roles for research listed earlier.

1. The results of the nation-wide survey carried out under the auspices of the Ministry of Health by Social Survey, which should become available this summer, should provide us then with a first broad picture of the pattern of mobility among the blind population of England and Wales.

2. Existing methods of aiding mobility in this country and the United States have been studied to some extent. One result of a visit to the United States in the Spring of 1964 was a strong recommendation to RNIB and St. Dunstan's that the Long Cane should be given a trial in this country, and that such a trial should include the provision of an expert instructor from the United States. The results of these trials are now a matter of public record (*St. Dunstan's Review*, October, 1965; *New Beacon*, December, 1965). Close contact is maintained with the various evaluation exercises which are at present being carried out with Professor Kay's ultrasonic aid all over the world. An extended series of observations of blind people using no aid, short canes, and/or guide dogs, covering familiar and unfamiliar routes has been started.

3. The present paper represents one aspect of the process of disseminating information in which we are concerned.

** International Research and Information Service for the Blind: Leslie L. Clark, American Foundation for the Blind, 15 West 16th Street, New York 11. British users contact RNIB, 224-8 Great Portland Street, London, W.1.*

4. Various programmes of research on fundamental problems of posture and of response to artificial as well as natural signals.

Appendix B

Wright's Mobility Rating Scale

The object of this scale is to have a single number by which to specify the level of mobility obtained by any person. It has to be used with considerable caution and is presented here as an example rather than as a generally accepted standard. It purports to rate mobility from 1-15, from completely independent mobility to complete lack of mobility. In doing so the authors have had to make a lot of assumptions about the relative merits of canes and dogs for instance, and one has to bear this in mind. They have also not yet incorporated anything about speed of travel because this has only become an explicit criterion fairly recently. But if you accept all this for a moment this is a scale of degrees of independent mobility. It is undoubtedly a useful quick way of describing and comparing different blind people.

Mobility Competency Scale

1. travels in familiar environments with no assistance
   travels in unfamiliar environments with no assistance
2. travels in familiar environments with no assistance
   travels in unfamiliar environments with a cane
3. travels in familiar environments with no assistance
   travels in unfamiliar environments with a guide dog
4. travels in familiar environments with no assistance
   travels in unfamiliar environments with companion
5. travels in familiar environments with a cane
   travels in unfamiliar environments with a cane
6. travels in familiar environments with a cane
   travels in unfamiliar environments with a guide dog
7. travels in familiar environments with a cane
   travels in unfamiliar environments with a companion
8. travels in familiar environments with a guide dog
   travels in unfamiliar environments with a guide dog
9. travels in familiar environments with a guide dog
   travels in unfamiliar environments with a companion
10. travels in familiar environments with a companion
    travels in unfamiliar environments with a companion

11. travels in familiar environments with no assistance
    does not travel in unfamiliar environments
12. travels in familiar environments with a cane
    does not travel in unfamiliar environments
13. travels in familiar environments with a guide dog
    does not travel in unfamiliar environments
14. travels in familiar environments with a companion
    does not travel in unfamiliar environments
15. does not travel in familiar environments
    does not travel in unfamiliar environments

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DEVELOPMENT AND ANALYSIS OF SOME TACTUAL MEASURES OF INTELLIGENCE FOR ADOLESCENT AND ADULT BLIND*

Eoline Christine Cull

The purpose of this project was to make some contribution to improved psychometry of the blind. Measures of mental abilities in which the subject would respond to tactual stimulation were created and tried out. The project was limited to the development and selection of measures over a difficulty level suitable for counseling with adolescent and adult blind. It was beyond the scope to make final tests of predictive validity or to secure extensive norming, although concurrent validity with other tests was sought on small samples.

Ten tests, to measure ability through the capacity of individuals to perceive and evaluate information received through manual-tactual channels, were developed from vinyl floor tile figures pasted on cards of pressed board. The aim was to measure capacity of subjects to identify similar or different figures, recognize the parts of a whole or the whole from its parts, discern figures in rotated or inverted positions, traverse a maze, identify similar figures across space, remember a figure over time, and transpose quarter-inch cubes from one box to another using various combinations of fingers. Two vocabulary and one space relation measure were selected as criterion standards.

Thirty sighted subjects responded to all items visually and tactually. They were randomly divided into two groups, one reacting to sight first, the other to touch. Mean scores for the groups were higher when the response was to visual stimulation. Individual differences in performance were obtained. The two groups were not significantly different in performance when they responded to the same types of stimulation, but the differences were significant when visual were compared with tactual responses.

Thirty legally blind subjects reacted to the same items. Eight of these had sufficient residual vision to influence performance and were placed in a subgroup for study. Performance by groups and subgroups of the blind were compared with tactual reactions of the sighted groups and subgroups. Scores of the blind with residual vision tended to be higher than those of either sighted group or the blind with no usable vision.

**This summary of the author's doctoral dissertation was published by the University of Southern California Graduate School in 1965.*

Principal component factor analyses with varimax orthogonal rotations were performed. A general-verbal-educational factor appeared in all groups. Age as a correlated variable loaded on this factor for the sighted but not so much for the blind. None of the tactual measures loaded on this factor for any group, showing that the measures appeared to sample other than verbal-educational ability. Factor organization for the tactual tests was unclear in the sighted subjects, the findings tending to be singlet and doublet factors not easy to interpret, except that in one case figural memory may have emerged. For the blind there appeared to be two interpretable group factors on the tactual tests, factors which may be tentatively identified as discrimination of shapes and visualization of movement of figures through space. The Space test, which was factorially pure in its preparation, was given to the sighted subjects. It tended to remain factorially aloof from the tactual tests, suggesting independence of visual and tactual domains, just as the latter seemed factorially apart from the verbal.

Within the limitations of this study it appears that tactual measures can be employed to test abilities of youths and adults. It is recommended that the study be continued so as to provide more information about the factorial nature of abilities in the blind, secure predictive validities of the measures used, and obtain adequate norms.

AN INVESTIGATION OF HUMAN VISUAL INFORMATION TRANSMISSION*

Ronald Joseph Massa

ABSTRACT

An empirical psychophysical study of visual information transmission is described. Attention is restricted to information transmission in "one glance," as measured by both total report (pattern reproduction) and partial report (sampling). Patterns and English letter arrays from a large, but finite, two-dimensional ensemble, subtending visual solid angles up to 10°, are the primary information sources. Information transmission rates are found to be a function of the pattern ensemble with total report transmission of 16 bits/exposure measured from 10-element patterns and 9 bits/exposure transmitted from 5-element patterns. The role of short-term visual memory in information transmission from the same sources is also discussed. A sampling technique for the psychophysical measurement of short-term memory storage and decay is described. The short-term memory is shown to be partially eidetic and capable of storing at least 2.5 times the information available in total report. It is concluded that the subjective classification of source patterns into "random" or "structured" groups provides a reliable basis for predicting performance in both total report and short-term memory readout experiments. Objective eye motion measurements indicate that the subject must rely on a single fixation point for exposures shorter than 125 msec; and that post-exposure movement is a function of the stimulus presented during the exposure. The role of dispersion and containment in performance is demonstrated and it is concluded that the same spacial distribution of related and unrelated items results in considerably different performance.

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1. INTRODUCTION

Man's interest in understanding the operation of his own sensory modalities, especially the visual modality, need not be discussed here. Today, as all phases of our technology advance, we wish to understand sensory modalities so we may emulate their operation, either to replace them in a handicapped human being, or to develop electronic or optical equipment that perform functions similar to human sensory functions. This interest in sensory operation has both resulted in the discovery of many new animal sensory functions and contributed to our understanding of the obvious ones.

Through the years many attempts have been made to enhance our knowledge of sensory systems. These studies may be broadly classified into two groups. One is predicated on the fact that the major interest in the sensory system lies in its *information-processing* role. Investigators concerned with this approach find it necessary to observe the internal activity of the human being or animal in response to excitation (usually external excitation) of the modality in question. Most such experiments are objective. An important class are neurophysiological experiments in which the representation of various visual stimuli in the nervous system is studied at the level of individual fibers or fiber bundles. Investigations of this nature--hundreds are described in the literature--while they have not given us many general operational or organizational principles of the visual modality, have contributed to our understanding of internal response to various sensory stimuli, and, in fact, have determined to a certain extent the electrical representations within the nervous system of various broad classes of visual and acoustic stimuli (1, 2, 3).

The second approach is behavioral or psychophysical. These studies are predicated on the fact that the human being acts as a transmitter of information. The simple block diagram in Figure 1.1 represents the human being merely as a "black-box" processor of sensory information. The human behaves or acts in response to visual stimuli. In many such experiments the subject is told how to act in response to various sensory stimuli, and inferences about his information-processing activities within any given sensory modality are made on the basis of how well he responds in the required manner to various external stimulus inputs.

The fundamental distinction between psychophysical and substantive information-processing experiments is that in the former the subject nearly always responds through a second modality. Thus, information-transmission experiments involve two modalities--the stimulated modality and the response modality. It is very difficult to draw inferences from psychophysical experiments about the processing of visual information at the level of the retina, optic nerve, or cortex. Furthermore, experimental artifacts introduced by the response modality, which are difficult to assess, often act as the ultimate performance-limiting factors.

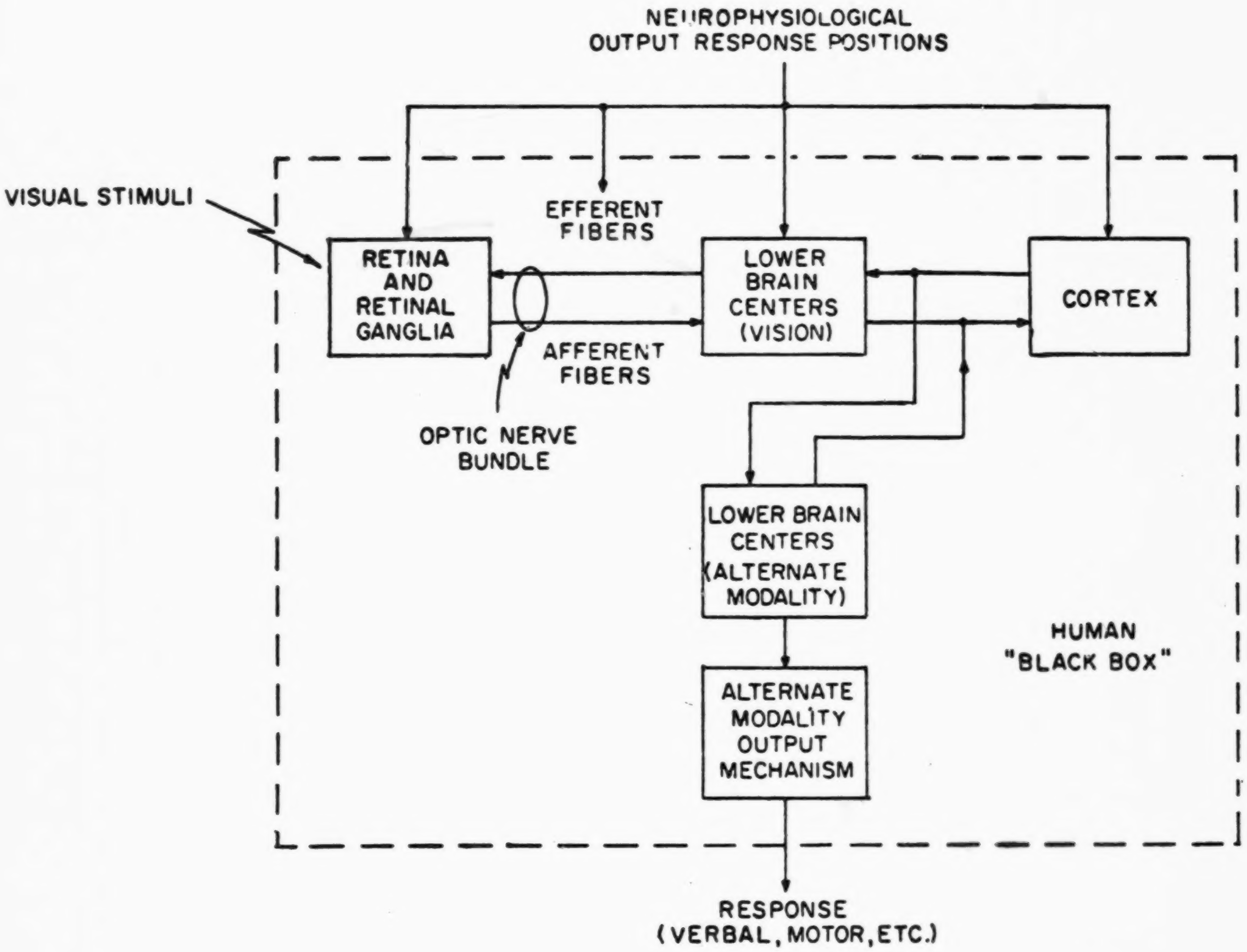
NEUROPHYSIOLOGICAL
OUTPUT RESPONSE POSITIONS
VISUAL STIMULI
EFFERENT FIBERS
RETINA AND RETINAL GANGLIA
LOWER BRAIN CENTERS (VISION)
CORTEX
AFFERENT FIBERS
OPTIC NERVE BUNDLE
LOWER BRAIN CENTERS (ALTERNATE MODALITY)
HUMAN "BLACK BOX"
ALTERNATE MODALITY OUTPUT MECHANISM
RESPONSE
(VERBAL, MOTOR, ETC.)

Figure 1.1. Sensory Experimentation Schematic

Several objective neurophysiological experiments have examined visual information processing in the retina (4, 5), optic nerve (6, 7), lower brain centers (8), and cortex [(9, 10); mostly in lower animals], without the manifestation of serious response modality artifacts. The relation between the results of these experiments and psychophysical experiments involved with gross information transmission is not well understood.

This thesis describes a direct, empirical study of human visual information transmission in very specific tasks. It seeks to define performance characteristics, organizational principles (valid at least for the small class of stimuli considered), and system aspects of the visual process that influence man's ability to process or act in response to certain visual information sources.

Similar investigations have been undertaken, including studies of the psychophysical response to acoustic stimulus (2, 11) and of tactile-kinesthetic senses (12, 13, 14, 15, 16). In each instance the desired experimental output may be expressed in terms of some quantitative measure of the human's ability to transmit information initially received through the auditory or tactile-kinesthetic senses. One particularly difficult problem in such experimentation is the quantitative measure of performance. Recent developments in information theory, beginning with Shannon's work, initially appeared to be very promising for extrapolation to psychophysical or psychological experimentation. Unfortunately the promise has proved superficial. It is often very difficult to assess information content of a stimulus or information transmission by a subject in terms of such well-defined quantities as bits per second.

In the course of this investigation, information-theoretic concepts are used where they appear to have a particularly interesting relationship to the experimental task or where they are required to relate results to other studies. These concepts and the calculations required to illustrate them are considered in Appendix D.

Much of the attractiveness of such concepts in psychophysical experimentation lies in the fact that the concepts of channel capacity information rates, and so forth, lend themselves very nicely to making quantitative models of various sensory processes. However, the question of model making in human or animal sensory processes is extremely complicated. First, an immense number of variables must logically be constrained or taken into consideration in derivation of any model. The role of many of these variables, while qualitatively obvious, is quantitatively unresolved.

Similarities between the visual sensory modality and the mathematical and physical channels treated in the study of information theory are in most cases obvious. The most striking similarity is in the qualitative operation of the visual channel. The human is capable of receiving and operating upon sensory information of increasing complexity with small increases in error rate. Ultimately a complete deterioration of performance occurs, and, in fact, the information transmitted and correctly acted upon decreases as the input rate exceeds some threshold value (17). This threshold value is often regarded as a form of "channel capacity" for the system.

In addition to the obvious similarities between the human visual channel and transmission channels, there are significant differences which have precluded the straightforward application of theory to the analysis of the visual system. The biggest difference is that most interesting measures of system performance (for example, perception) are subjective and thus do not lend themselves to precise mathematical representation. Furthermore, the capacity of a human sensory channel is a function of so many variables that mathematical models have decidedly limited application at the present time. With these facts in mind, we are forced to conclude, as Quastler does (17), that rigorous methods cannot yet be employed in the study of sensory operation or sensory channel capacity.

At least one worker--Jacobsen (18, 19)--however, has applied formal methods to the study of the channel capacity of the human eye and ear. He has selected for analysis only those portions of the system that are not primarily subjective--that is, structure--and the resulting bit figures are more properly considered as ultimate capability rather than operational capacity figures.*

This thesis is concerned primarily with the human's ability to extract information from dispersed visual patterns, not with the concept of visual channel capacity. Thus it is focused on the operational features and the size of patterns and the relationship of their elements, all of which modify ability to extract information from them. The experimentation is psychophysical in nature, except for a few experiments intended to illustrate aspects of the human visual system, which one might class as "mechanical" or "system" aspects. Such things as the size of the pattern and its role in perception, the light-versus-time sensitivity of the human eye, and the speed with which the human eye must track to derive information are ordinarily not treated in psychophysical pattern-recognition studies. Therefore, it is the author's hope that this work represents a sensible beginning to an intermediary study--that is, one somewhere between the very basic bit rate figures such as have been derived from the experiments of Miller, Brunner, and Postman (20) and others (21) and the complex normal visual

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**Jacobsen estimates a bit capacity of 4.3×10^6 bits for the eye and about 5 percent of this figure for the ear.*

situation encountered in everyday life, where we must contend with an infinite pattern ensemble, colors, the gross motion of the subject, the wide range of dynamic light intensities, and many other factors whose influence must be understood before we can truly have a feeling for the operation of human vision.

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2. SOME RELEVANT ASPECTS OF HUMAN VISUAL INFORMATION TRANSMISSION

In this section a framework is established for the experiments that follow. Several aspects of visual communication are recalled from the literature, and some ideas pertinent to the problem are interjected by the author.

This research does not seek to solve the momentous problems of what or how humans see. Rather, it approaches a single and narrow but significant problem in visual communication, which the author chooses to call the one-glance problem--the problem of the transmission of visual information gathered through a single exposure to a given visual stimulus.

2.1 The One-Glance Problem

In normal visual situations the human receives and acts upon visual information received through a series of related glances at a visual field extending over more than 180 deg in the horizontal direction and 100 deg in the vertical direction. Visual acuity is not uniform over this entire field for all positions of the eyes. Presumably, the only portion of the visual field that projects on the foveal area of the retina is portrayed with the full resolution capability of the visual system (1). This solid angle of foveal vision is surprisingly small. While accurate figures are not reported in the literature, it is safe to assume that foveal vision occurs over a solid angle of less than 5 deg. The remaining solid angle of vision for any eye position is called the peripheral angle.

It is particularly convenient for our purposes to define the limits of the one-glance problem independent of stimulus duration or spacial extent--bearing in mind, of course, that any such definition will allow both temporal and spacial effects to become significant factors of performance. We define the one-glance problem as the information-transmission problem characterized by a single exposure to a visual stimulus, with report by the subject beginning after the stimulus exposure is over. To avoid undue complications, the one-frame problem is restricted to stimuli well above threshold intensity; stimulus duration is selected in accordance with the considerations outlined in the following paragraph.

We can state, at least qualitatively, that in visual information-transmission tasks performance as a function of stimulus duration and the spacial extent of the information source is as shown in Figure 2.1. For stimulus intensity (S_0) well above the stimulus intensity threshold (S_{crit}), performance will ultimately reach zero as the duration of the stimulus approaches zero.* Details of performance in various tasks during this intensity integration region are reported by Hunter and Sigler (2) and Hartline (3). For the intensities used throughout this research the lower end of the one-glance region is at an exposure of less than 10 msec (T_{min}).

In Figure 2.1 the longest duration of the one-glance region is about 3 sec (T_{max}). The choice of T_{max} is somewhat arbitrary. The figure 3 sec is chosen for three reasons.

1. It is difficult for subjects to remain fixated for longer than 3 sec without eye blinking and head motion.

2. It is difficult to prevent a partial report or other artificial stimulus encoding for durations longer than 3 sec.

3. In most information-transmission tasks the subject can gather much more information in 3 sec than he can "remember" for reporting.#

This is the only situation considered here. Stimulus intensity was not a variable; all information sources were presented at light intensities well above threshold for which all parts of the stimulus could be clearly seen by all subjects for all exposure durations.

#*This point is discussed at greater length in section 2.3.*

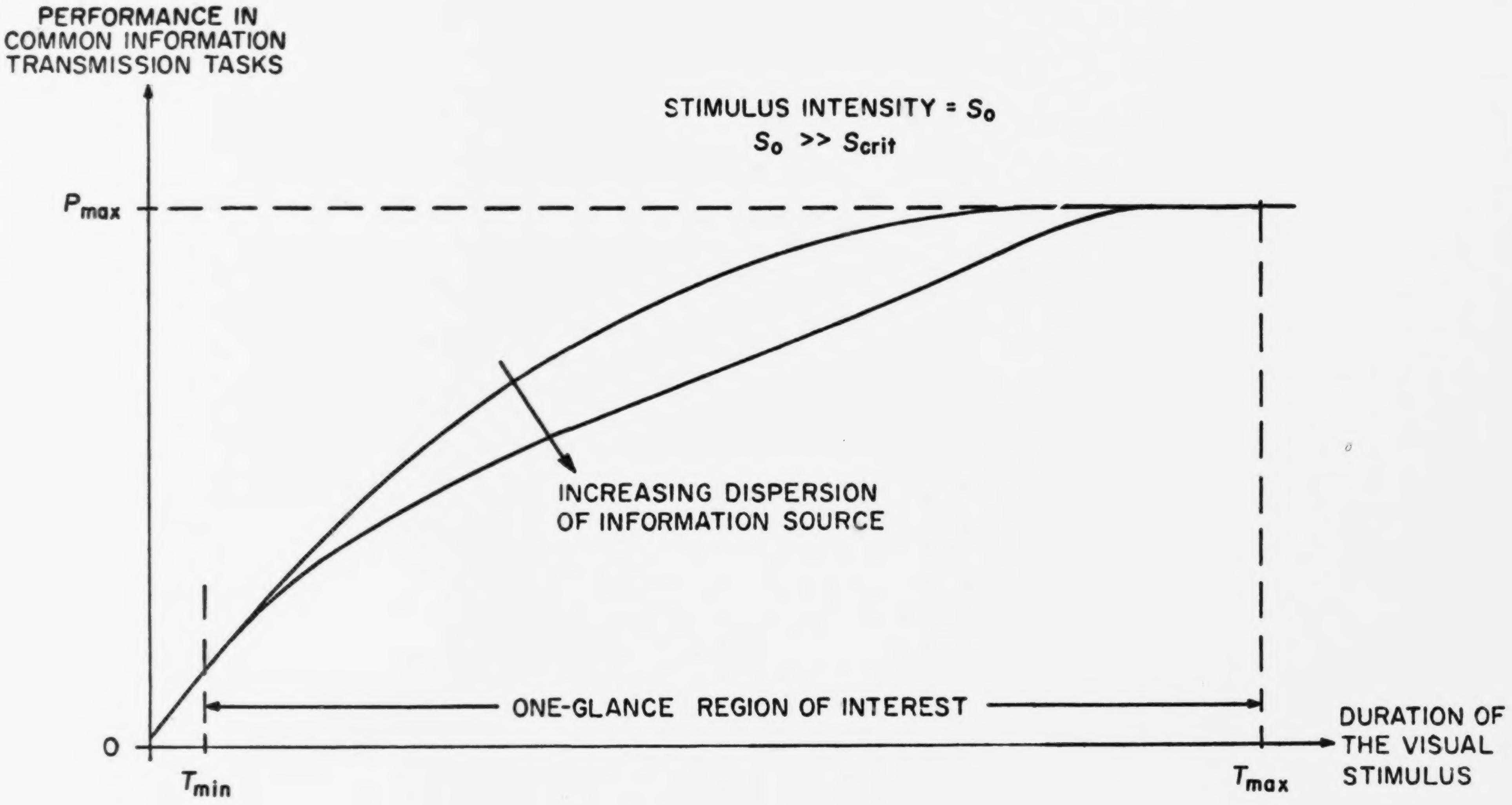


Figure 2.1. The Qualitative Description of Performance in One-Glance

In the region of interest between $T_{\min}$ and $T_{\max}$ performance from sources with the same information content is critically dependent upon the source dispersion. This dependence is most readily illustrated in the extreme. Projection of a single 1-in.-high English letter (from a large ensemble) at a distance of 2 ft for a duration of 10 msec would result in recognition nearly all the time by all subjects. The same letter 2 ft high would be quite difficult to recognize in such a short-duration exposure. Thus, the one-glance problem is the transient problem of information-transmission for short exposures; it is temporally bounded by energy integration and span of memory regions and critically dependent upon dispersion of the information source as well as its detailed nature.

An interesting class of experiments, which does not emphasize temporal or transient aspects of the recognition problem, is exemplified by Julesz' work (12). Julesz attempted to determine which patterns are seen and which are not, given extremely long exposure durations; hence his are steady-state, or long-term, visual pattern recognition experiments. A qualitative similarity between Julesz' work and this research is discussed in section 3.4.

Short-duration information transmission from arrays of English letters is treated in some detail by Sperling (4) and by Miller, Brunner, and Postman (5), among others. And Klemmer (6), Frick (7), Pollack (8), and others have considered short-term information transmission from linear arrays and matrix arrays. In general, these experiments use small-dimension pattern sources projected to subtend small angles of vision.

A 9 × 12 matrix is used in this examination of the one-glance problem. This ensemble permits much greater freedom in choice of patterns and provides for separation of the pattern-registration problem from the *pattern-recognition problem*. In smaller ensembles the external boundaries of the visual field provide artificial clues which modify the problem of pattern recognition significantly. While it is advantageous to retain these boundaries to simplify the pattern-reproduction problem by the subject, the size of the ensemble still permits adequate separation of registration and recognition effects.

Patterns selected by filling in some of the squares from the 9 × 12 pattern matrix were used in a pattern-recognition experiment. Two types of patterns were chosen by filling in either five or ten of the 108 available positions. Patterns with five filled-in squares are referred to as (5)-patterns, and so forth. The number of filled-in elements (n) was selected to provide for classes of patterns.

1. (5)-patterns with widely dispersed, nonsymmetrically placed elements which appear as five dots in a large matrix field.

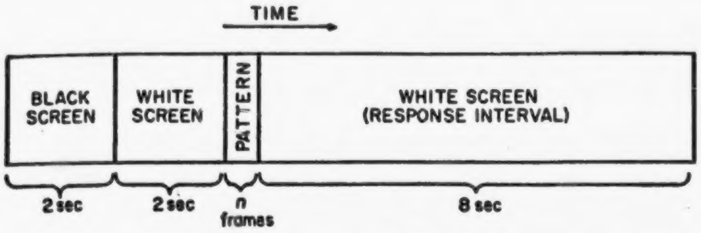
2. (5)-patterns with closely spaced, symmetric, or patterned elements which are relatively easy to reproduce.

3. (10)-patterns that appear as a high density of arbitrary squares close enough to be related to each other, but not conveying a unity of construction.

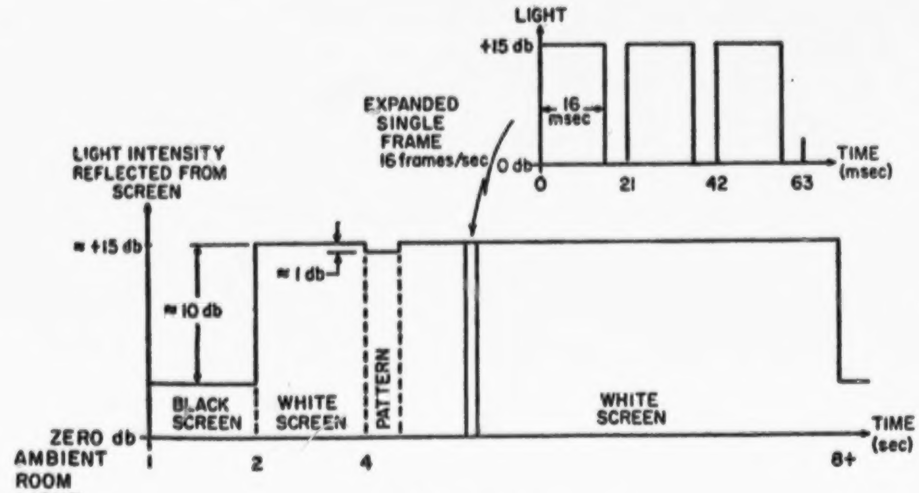
4. (10)-patterns formed into common shapes or figures.

Photographs of sample (5)- and (10)-patterns are shown in Figure 2.2 exactly as they were presented to the subjects.

Unfortunately, the grid lines must be projected along with the pattern for experiments in which subjects are required to reproduce the stimulus. The absence of grid lines allows the subject too much "artistic license" in making his report. Size distortions too difficult to "grade" result. The matrix lines are drawn so that the outer border is the dominant feature, with the interior lines still clearly seen on exposure.


TIME
BLACK SCREEN
WHITE SCREEN
PATTERN
WHITE SCREEN (RESPONSE INTERVAL)
2 sec
2 sec
n frames
8 sec

(5)-Pattern


LIGHT
+15 db
16 msec
0 db
0
21
42
63
TIME (msec)
EXPANDED SINGLE FRAME 16 frames/sec
LIGHT INTENSITY REFLECTED FROM SCREEN
≈ +15 db
≈ 10 db
≈ 1 db
BLACK SCREEN
WHITE SCREEN
PATTERN
WHITE SCREEN
ZERO db AMBIENT ROOM LIGHT
1
2
4
8+
TIME (sec)

(10)-Pattern

Figure 2.2. Pattern Matrix and Sample (5)- and (10)-Patterns

2.2 The Effects of Pattern Dispersion

Unlike most experiments for short-duration stimulus presentations, the displays used in this thesis generally subtend angles up to 10 deg. Patterns of this size are sufficiently dispersed to require gross eye motion for perception. This freedom in stimulus choice has some significant effects on performance. Some of these effects are illustrated in sections 3.3, 5.2, and 5.3.

Generally, the effects of pattern dispersion are not well known. It is not difficult to appreciate the qualitative effects of dispersion in the one-glance problem (see section 2.1). However, several questions arise. Are dispersion effects different in the horizontal and vertical directions? Is there a spacial span of apprehension (analog of the number of items that can be remembered from the same spacial "point") as a function of exposure time? How are the answers to these questions modified by the pattern material?

While assessing the quantitative effects of dispersion is not a primary objective of this work, some data regarding objective measures of eye motion and horizontal and vertical dispersion effects are included in sections 5.1 and 5.2 and Appendix C.

2.3 Information-Transmission Report Techniques

Once subjects have been exposed to visual stimuli with some information content, how does one require them to report the information perceived during the exposure? Nearly all psychophysical reports involve another modality which introduces report artifacts.* Ignoring report difficulties for the moment, an interesting limitation occurs in information-transmission experiments. Miller has eloquently stated that the span of immediate memory--the store from which report information may be drawn--can handle about ten "items" at the most (9, 10). Thus--regardless of the information content of a stimulus in bits, which actually impinges upon the retina, progresses along the optic nerve, and is processed in the higher brain centers--only a certain portion of this information can be reported: the information the subject can encode into about five to ten "items." This limitation is not as severe as it sounds. The redundancy, or information shared among the elements of a visual stimulus, can be expressed in terms of our ability to encode the stimuli into some fixed number of items after relatively long exposures.

Averbach and Sperling have shown that this span of immediate memory# limitation holds only for total report--that is, reporting

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**An example of a report artifact which is an experiment limitation of significance is discussed in section 5.3.*

#The term "span of immediate memory" is somewhat misleading. Immediate memory has been demonstrated to decay very slowly (11), remaining essentially unchanged for minutes or hours in some instances.

everything in the stimulus or reproducing the stimulus (11). They describe a technique for measuring information available earlier in the information-processing chain, perhaps in the retina itself. In general, they conclude that ". . . the visual process involves a buffer storage of relatively high capacity that can take in information virtually instantaneously and retain it to permit its relatively slow utilization." They estimate storage capacity of this buffer at greater than or equal to 70 bits, with storage decay from 1/4 to several seconds.

Both techniques--total report and short-term memory sampling--are used in this research to assess pattern-recognition principles for the ensemble described earlier. The results differ significantly, supporting the conclusion that short-term memory stimulus processing is conducive to higher information transmission. In fact, the interaction of high-capacity short-term memory between related glances is probably a very fruitful area for research aimed at understanding the human's apparent high information-processing capability in normal perceptual situations.

Total report is implemented in several experiments described later by requiring the subject to reproduce exposed patterns in a similar field. A sampling technique for estimating pattern perception in the short-term memory is described in section 4.2. The relation between span of immediate memory for independent items from a visual stimulus to related pattern elements is described in section 3.5.

2.4 Experimental Technique

A technique for the presentation of short-duration visual stimuli using an ordinary 8 mm motion picture film has been developed and used for many of the experiments reported later. Because the mechanism of projection results in an intensity-versus-time characteristic significantly different from that of a projection tachistoscope, some remarks regarding this technique are in order.

A typical short-duration pattern presentation employed with a motion picture projection technique is shown in Figure 2.3. The subject is called to attention by a 2-sec dark interval on the screen. Following the dark interval, a flat white, or background, sequence is projected for 2 sec; then the pattern is exposed on the white background for 1, 2, 5, 10, or more frames. Immediately after the pattern exposure, the qhite background is projected for 8 to 10 sec; during this period the subject makes his report, generally in writing. The light reflected from the screen provides ample illumination for a written report.

The projection technique results in the light-versus-time curve shown in Figure 2.4. This curve is measured (approximately) with a photographic light meter which monitors reflected

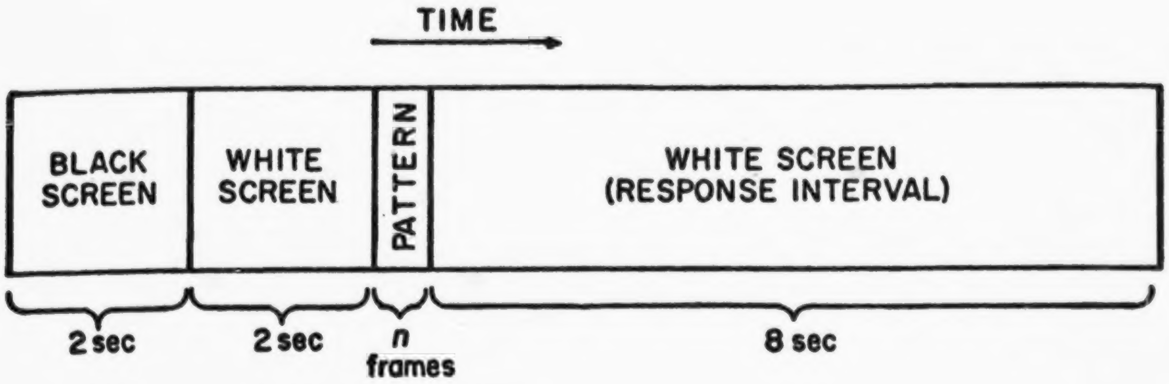
TIME
BLACK SCREEN
WHITE SCREEN
PATTERN
WHITE SCREEN (RESPONSE INTERVAL)
2 sec
2 sec
n frames
8 sec

Figure 2.3. Typical Motion Picture Pattern Exposure

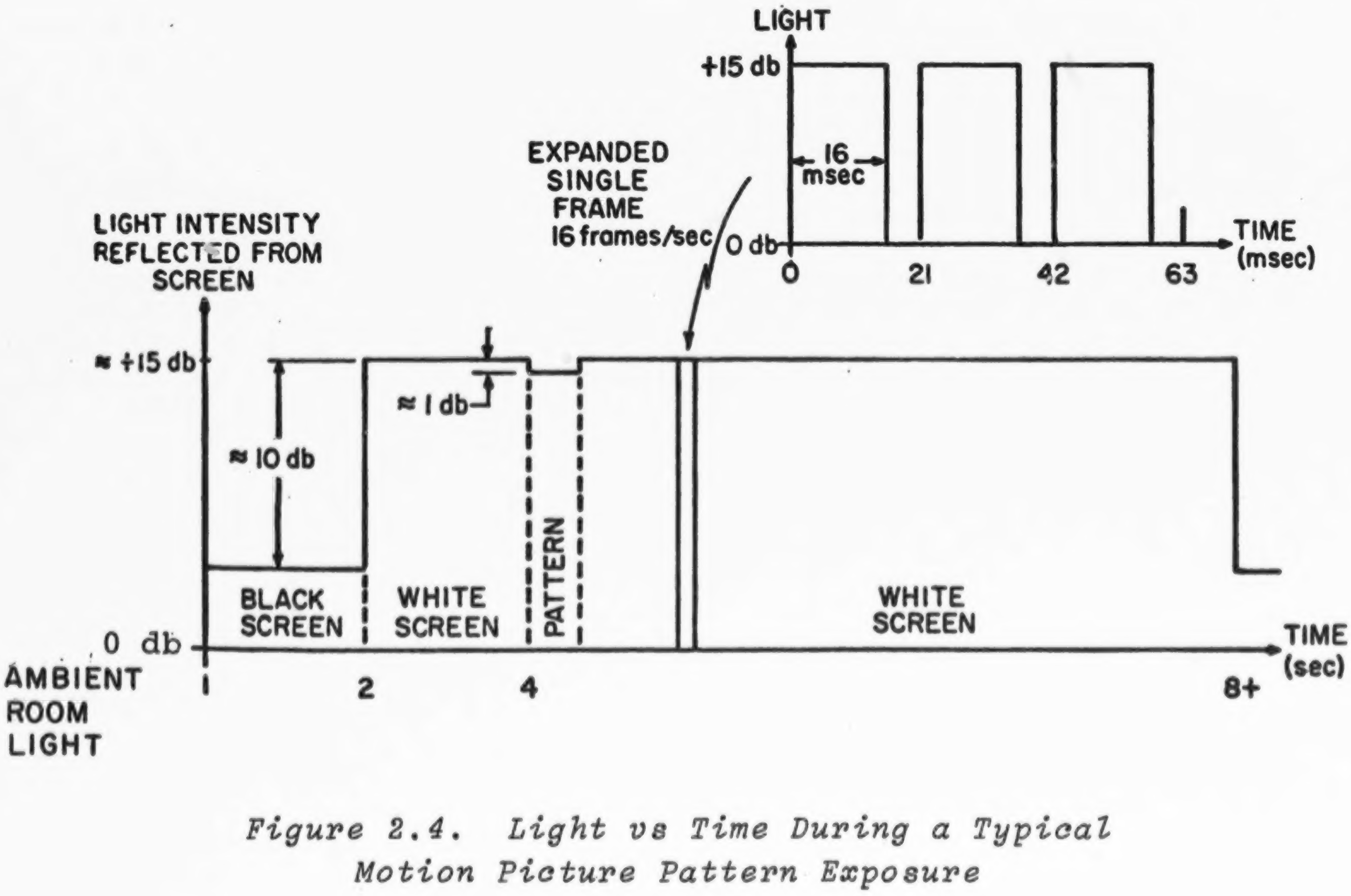

Figure 2.4. Light vs Time During a Typical Motion Picture Pattern Exposure

lig. : from a common glass-beaded screen. A Bell and Howell 8 mm LUMINA 1.2 projector with f1.2 Zoom lens was used. The room light level was about 15 db below peak light during white background frames, and the dark background preceding the pattern, used for call to attention, was about 10 db below peak light level. The small decrease in level during a pattern exposure is caused by blacking by the pattern elements.

The significant difference between a motion picture and tachistoscope presentation is evident in the single-frame expansion graph at the top of Figure 2.4. At an exposure rate of 16 frames/sec, the projection lamp is shuttered at 48 cycles/sec, essentially chopping the light into three distinct pulses. This light presentation requires at least a duty cycle weighting factor for comparison with single light pulse tachistoscopes at the same light intensity. The light-to-dark ratio within a single frame varies somewhat with the projection speed. This has been measured at 3.3:1 for the slowest speed setting and 3.5:1 for the fastest speed setting with the Bell and Howell LUMINA 1.2 projector.

The light-time characteristic of motion picture projection has several advantages over tachistoscope projection. Its major disadvantages are that time quantizing must be used (in terms of frames of exposure) and that exposures below 60 msec are generally difficult to achieve without special equipment. The advantages include ease of experimentation, the possibility of testing several subjects at once, timing ease for multiple-exposure experiments, and ease in the generation of a wide variety of preexposure and postexposure fields.

The question of preexposure and postexposure fields and the generation of afterimages, which materially change the effective exposure duration, has been discussed by several workers (11, 13, 14). The white preexposure and postexposure fields used in the experiments described later in conjunction with motion picture presentations appear to be minimally conducive to afterimage formation.* (This point is discussed further in section 4.) Furthermore, manifestations of the Broca-Sulzer phenomena (15) demonstrated in part in tachistoscope experiments discussed in section 5, are not apparent with the motion picture display.

It is, of course, well known that normal flicker-fusion occurs at a much lower frequenty (16) than that implied at a 16-frame/sec exposure rate--the rate used throughout this work. The subject cannot distinguish these from tachistoscope presentations.

**This should certainly be the case because afterimage formation could seriously interfere with motion picture quality.*

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3. PATTERN RECOGNITION IN ONE GLANCE—TOTAL REPORT

Results of pattern-recognition experiments requiring total report by the subject are presented in this section. Total report, or pattern reproduction, is a psychophysical process which is different from pattern recognition in the short-term memory (treated in the next section). The experiments described in this section involve only the finite pattern ensemble discussed in section 2.2. In general, the results are presented by experiment; generalizations made in later sections of this chapter are supported on the basis of the experimental data. To point out contrasts implicit in the relationship between pattern elements, some letter-report data from spacially distributed arrays involving total report are also presented. A compilation of experimental data by subject, or other appropriate delineation, is included in Appendix B.

The general objective of this section is to illustrate general organizational techniques employed by the human when faced with a pattern-recognition task involving total report. Estimates, where applicable, of information rates (see Appendix D) are in general agreement with published figures regarding the maximum visual information intake in other tasks. Some general statements, difficult to quantify, but typical of general performance in a task of this nature, are also included.

The reader should recall that stimulus intensity--that is, light level--is not a parameter in any of the experiments described in this work. Light levels used are substantially above threshold and result in experimental exposures that are clearly seen and clearly read by all subjects.

3.1 Information Sources

The basic information source used for the pattern-recognition and pattern-organization experiments is the 9 × 12 pattern matrix described in section 2.2. Two sets of patterns have been created from this basic matrix ensemble. One, the (5)-set, has been generated by filling in five of the 108 squares with clear black coloring. The second, the (10)-set, has been created by filling in ten such matrix elements. Figure 3.1 depicts the ten (5)-patterns (lettered A through J) and the ten (10)-patterns (numbered 1 through 10) used for the basic pattern-recognition experiments. It can be seen that these patterns vary with respect to any *a priori* notion of complexity within each set. For instance, some of the (10)-patterns are highly structured or formed, while others appear decidedly random. These basic twenty patterns were used in connection with short-time motion picture displays as the basic pattern-information sources, or spacially distributed arrays.

This set of patterns provides for sufficient flexibility in separating the problem of pattern recognition (that is, observing

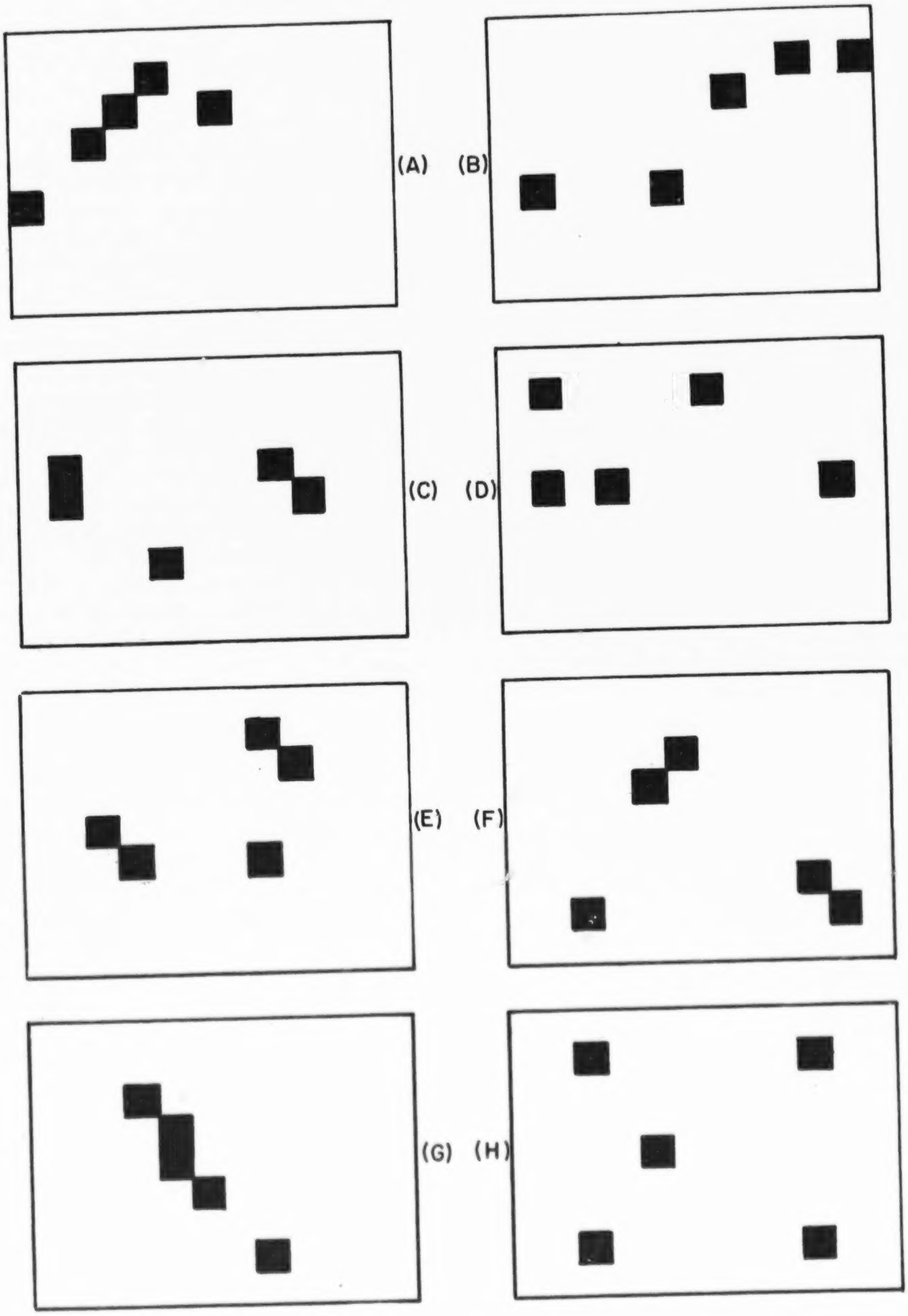

Figure 3.1. (5)- and (10)-Patterns--Sheet A

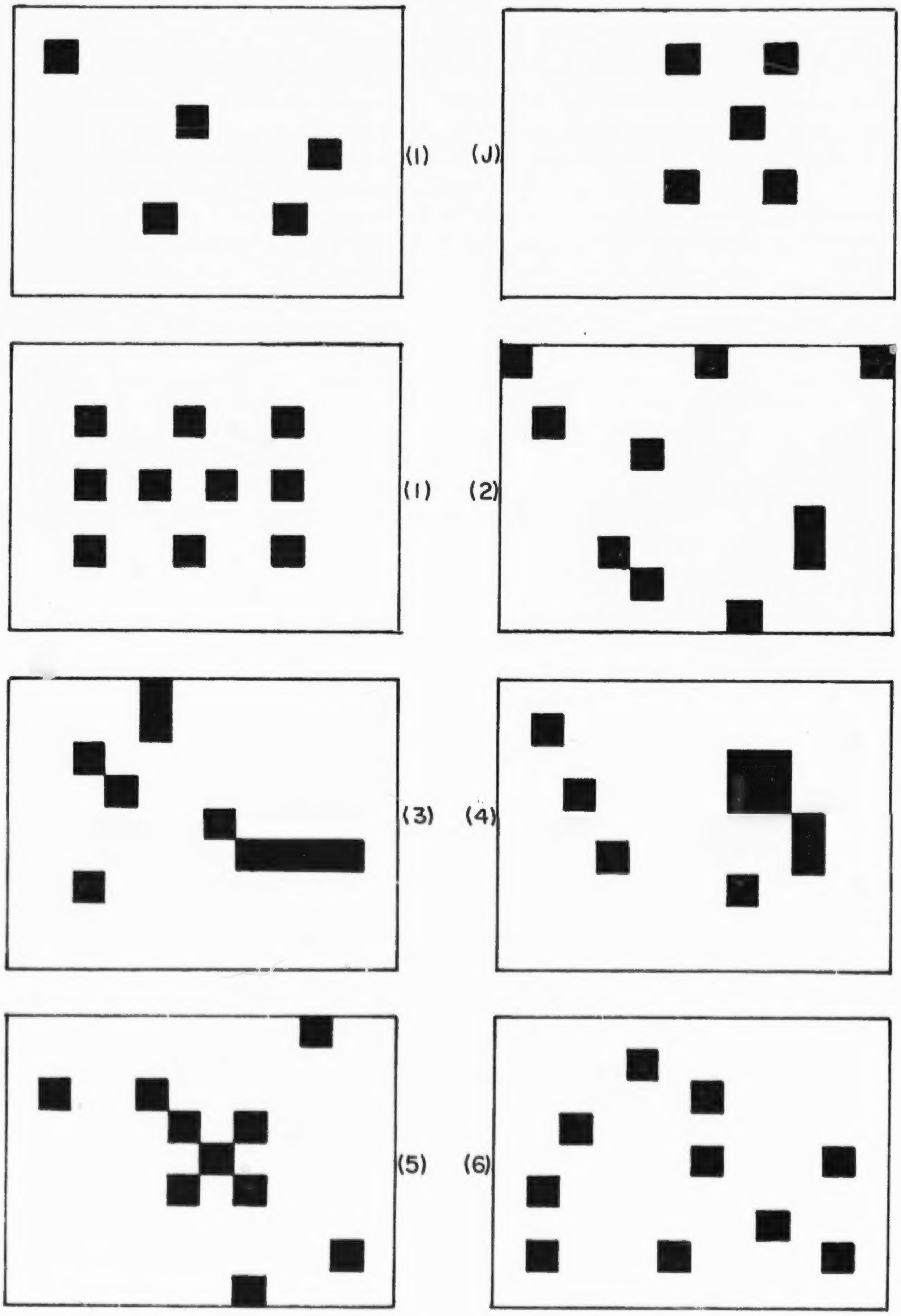

Figure 3.1. (5)- and (10)-Patterns--Sheet B

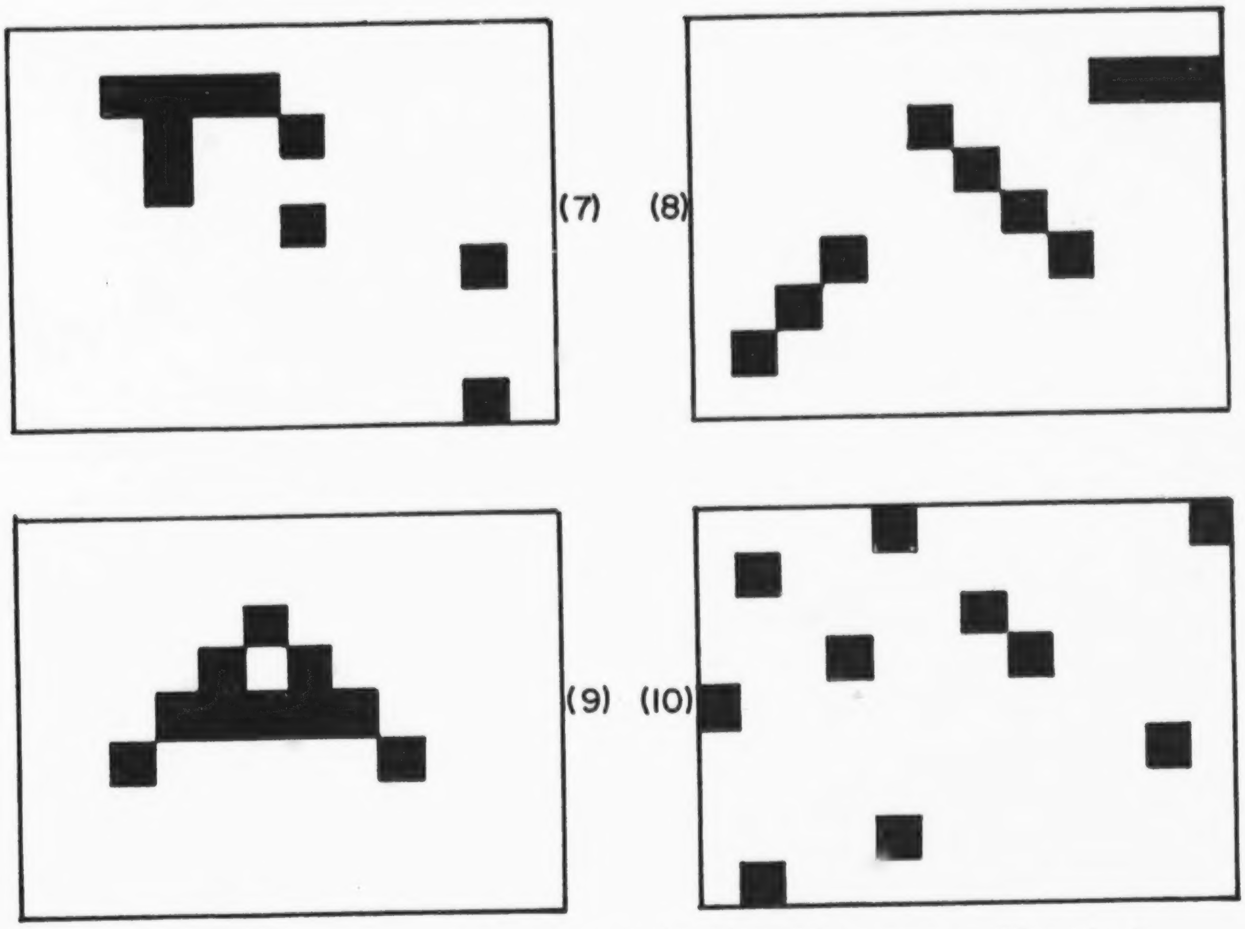

Figure 3.1. (5)- and (10)-Patterns--Sheet C

and reporting the correct relationship between the elements themselves) from the problem of pattern registration (that is, the correct placement of the pattern elements within the matrix ensemble). In fact, for most patterns the basic pattern can be written down completely correctly with considerable registration error. Furthermore, the simple black and white patterns exposed to subjects are clearly seen, and, despite the grid lines which are always present during exposure, the basic patterning effect (recognition) is the main psychophysical report phenomenon.* (Throughout the remainder of this study patterns are referred to either by letter or by number as in Figure 3.1.

3.2 Classification Experiment

In connection with the results of pattern-recognition experiments for total report, a preliminary experiment was conducted in which subjects were asked to classify the twenty test patterns.

**Figure 3.1 does not show the grid lines on the patterns. This is merely for convenience in portraying the figures. For all exposures the grid lines were included, with the major dark heavy line approximately 1/8 in. in diameter around the outer border of the pattern and the grid lines about 1/5 of this thickness (see Figure 2.2).*

Experiment 1

Twenty subjects, male and female between the ages of twenty and thirty, were individually shown all twenty test patterns. The patterns were arranged on a table in alphabetic and numerical order. Subjects were given the following instructions: "On the table before you there are twenty sheets of paper. The ten sheets of paper on the left are lettered A through J. The ten sheets of paper on the right are numbered 1 through 10. The difference between the lettered sheets and the numbered sheets is that the lettered sheets all contain patterns formed by filling in five of the 108 little squares on the sheet of paper. The numbered sheets, 1 through 10, all contain patterns which are formed by filling in ten of the 108 squares within the matrix frame.

What I would like you to do is to write the letters A through J down the left-hand side of the sheet of paper you have been given and the numbers 1 through 10 down the middle of this sheet of paper. I want you to classify, to the best of your ability, each and every pattern into one of two classes by placing the letter 'R' or the letter 'S' next to the letter or number that describes the pattern. I want you to place the letter 'R' next to the pattern number or letter if you feel the pattern is 'random.' Place the letter 'S' next to the number or letter of the pattern if you feel that particular pattern is 'structured.' I offer you no further definition of the words 'random' and 'structured' other than what these words may connote through their everyday meaning to you. One other additional bit of information to enable you to make your classification is that I want the patterns classified in such a way that neither set is empty--that is, there is at least one 'random' pattern and one 'structured' pattern in each of the two sets of ten patterns. Are there any questions?"

The subjects were then left in the room alone for as long as they desired to make their classification.

Most subjects were able to perform Experiment 1 with little or no difficulty; on the average, about three to five minutes were required to complete the task. Results of this classification are presented in Figure 3.2. The subjects were more certain with the (10)-patterns--that is, more of them agreed as to their classification. Most subjects reported that it was difficult to classify many of the (5)-patterns; indeed none of these patterns was classified either 100 percent structured or 100 percent random.

Many subjects indicated different criteria for judging "R" or "S." Considering the different techniques or criteria used to make this discrimination, it is surprising that so many subjects agreed on so many of the patterns. These structured-random distinctions, made without any time

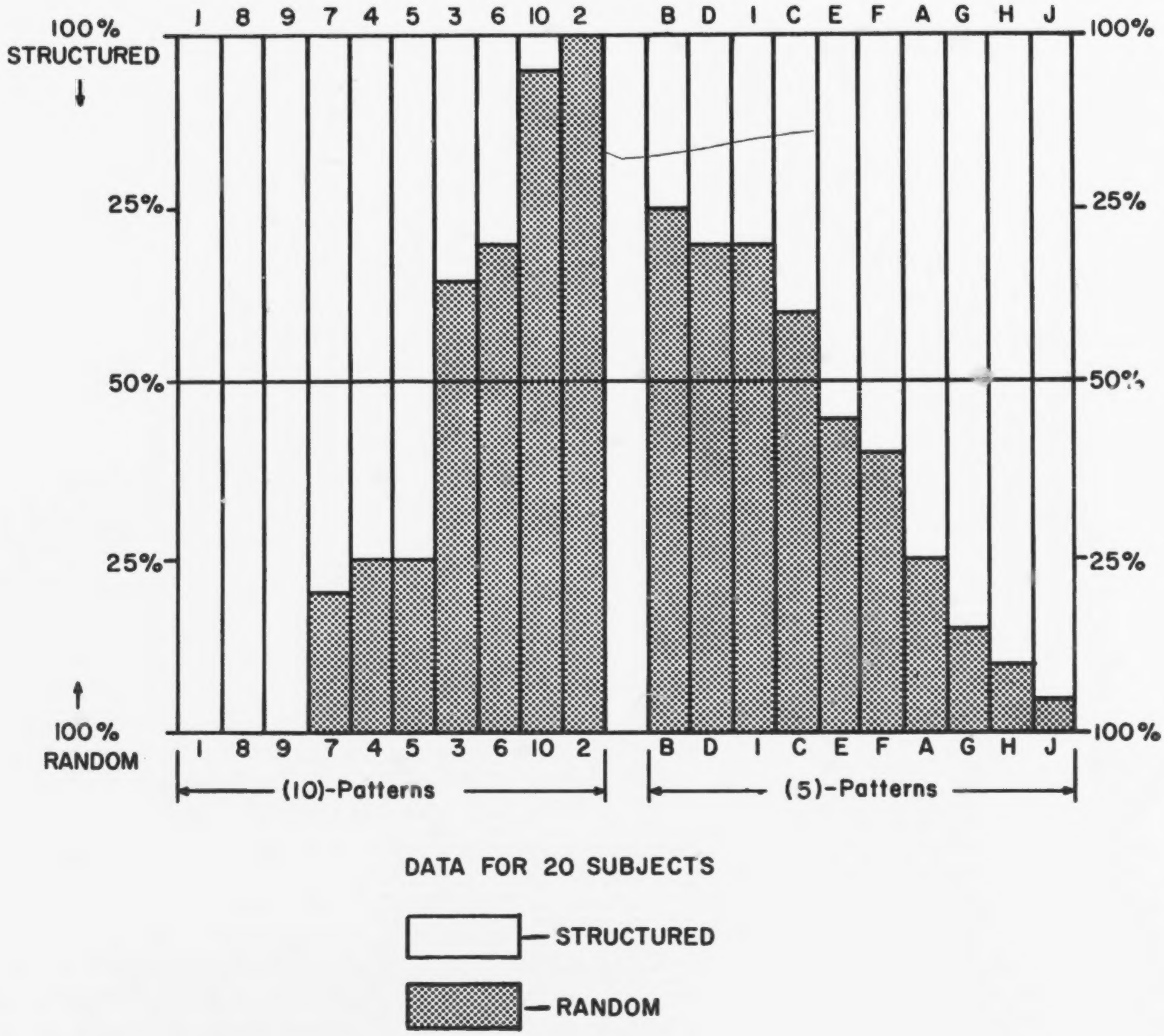

Figure 3.2. Classification of Patterns--Experiment 1

restriction or without stringent definition of the basis for classification, are closely related to performance in later pattern-recognition tasks involving the time domain--that is, short-duration exposures. This relationship is considered significant.

On the basis of the results of Experiment 1, we can group the various patterns into structured and random sets. The reader should refer to the patterns as he studies the results (Figure 3.2); he can compare his with the subjects' notions as he attempts to see the pattern features that influenced the classification.

Of the twenty patterns, only four [(10) and (6), (B) and (I)] were actually chosen from a random number table; all others were constructed by the experimenter. Several subjects volunteered the information that (6) was very difficult to classify because eight of the ten elements are apparently "connected" by a smooth curve which starts from the lower left element and proceeds upward.

3.3 Pattern-Recognition Experiment--Results

In connection with pattern recognition in one glance with total report, the following comprehensive pattern-recognition experiment was conducted.

Experiment 2

Seven subjects, five male and two female between the ages of twenty and thirty, were exposed to 120 test patterns involving each of the twenty patterns in Figure 3.1 at exposure durations of 1, 2, 5, 10, 20, and 50 frames of a motion picture film projected at 16 frames/sec. Each subject was approximately 9 ft from the screen (viewing a pattern on the screen which subtended an angle of about 8.8 deg). The subjects were given an answer sheet on which 120 matrices (six to a single 8 1/2 in. × 11 in. sheet) were printed. Each matrix was numbered. Every fifth pattern was numbered (in order to provide some reference should the subject miss one of the short-duration exposures). The subjects were instructed to mark X's in those boxes within the matrix in which a black square appeared during each of the short-duration exposures. The exposure sequence shown in Figure 3.3 was used throughout the experiment. In general, there was ample time for the subject to make his report. The experiment was conducted in one session with a five-minute break between the sixtieth and sixty-first pattern exposures. The session, including the break, lasted approximately 45 min.

Several practice patterns at the beginning of the film were exposed and several patterns within the film were redundant in order to provide some measure of the stability of output of such an experiment. The subjects found the task difficult. The major difficulty encountered by the experimenter was in preventing the subject from making a partial report before the long-duration (50 frames-3 sec) exposures disappeared from the screen. Subjects were instructed to try their best to register the pattern; guessing was discouraged. Seldom did they respond by marking in more squares than were actually projected for any given pattern. They were not permitted to see the pattern ensemble beforehand, nor were they told that the patterns consisted only of five and ten filled-in squares. Generally, this was discovered very early in the game. Furthermore, the patterns, arranged in a random order with respect to both pattern and duration of exposure, were not conducive to learning. Although it is quite simple for the average subject to recognize some of the patterns he has seen before, this factor did not materially improve performance.

Two grading techniques were employed in determining the results of this experiment. The experimenter first recorded "absolute registration data." A clear plastic overlay with the correct squares marked was placed over the response sheets and the number of coincidences--that is, the number of times a square was correctly registered--was recorded. This figure was called the absolute registration grade for the pattern exposure point. For the (5)-patterns the grades vary from 0 to 5, and for the (10)-patterns, from 0 to 10.

The second grading technique is the one of primary interest in deducing pattern-recognition characteristics and organization. It was an arbitrary "best-fit" technique devised by the author to provide some basis for separating of pattern-registration and pattern-recognition effects. This technique was implemented in the following manner. The plastic overlay was shifted to provide the maximum coincidence or correlation between the correct pattern and the subject's response. Correct registration due to shift was employed in a special sense. For example, if a subject had three squares of a (5)-pattern appropriately registered (such as the example shown in Figure 3.4) and had at least one coordinate of either of the remaining two squares with respect to the three properly registered correct, he was given credit for that square. Figure 3.4 illustrates the typical pattern grade with the correct answer and subject response delineated. This technique for best match, although completely arbitrary, provides a basis for separating recognition and registration effects. Initially, the author was

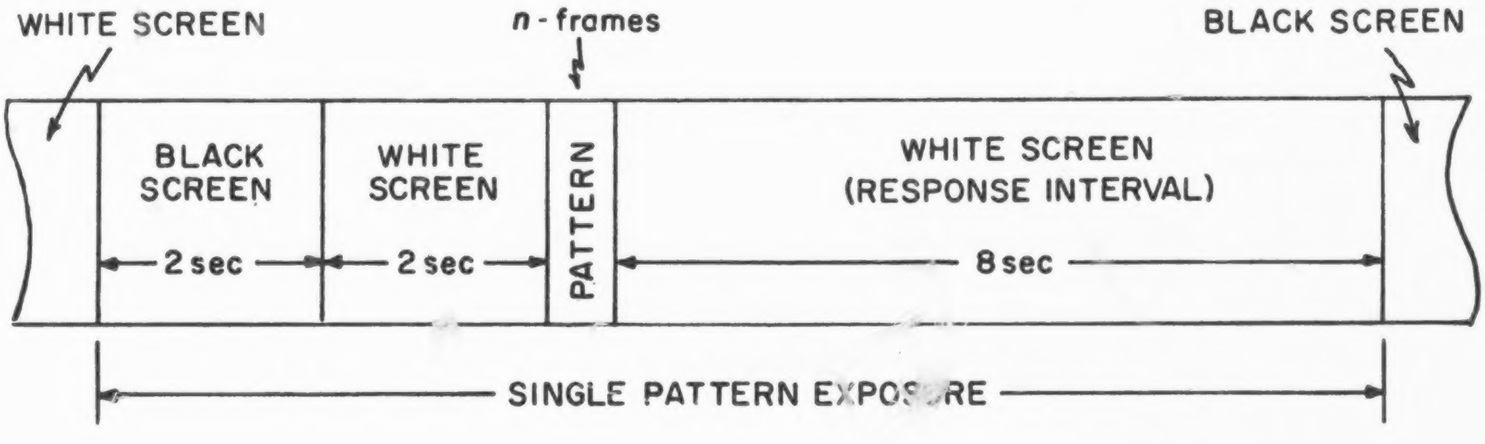

Figure 3.3. Projection Sequence--Experiment 2

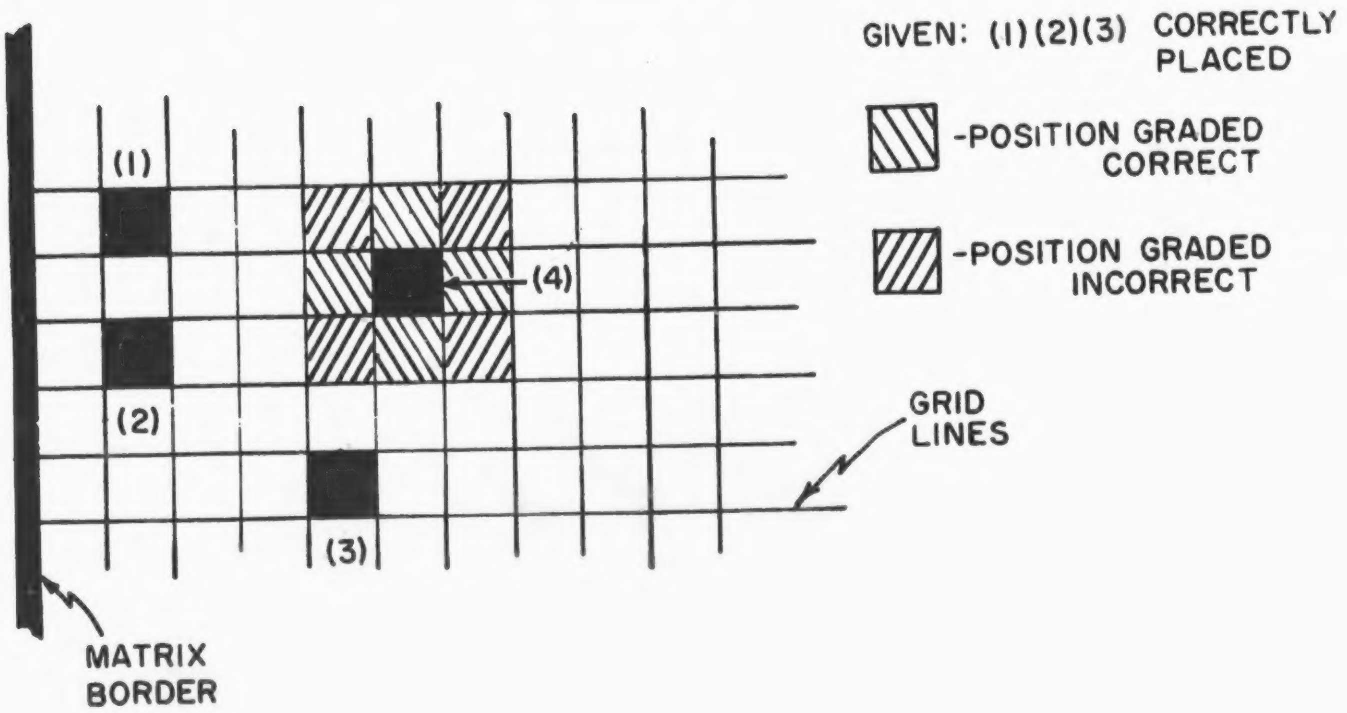

Figure 3.4. Best-Fit Grading Example

concerned over types of answer distortions other than those covered by the simple definition of best-fit grading. For instance, what would be the grading procedure employed if the subject had expanded or contracted the size of the pattern in such a way that the technique for best-fit was not applicable? In only about thirty of the 840 pattern responses was there any doubt as to what grade to assign, and in most instances doubt involved only one square. Furthermore, the experimenter described the rules for best-fit grading to a naive assistant and several grades were determined by both experimenter and assistant. There was complete agreement between the experimenter's and the assistant's grading. While such agreement does not assure aptness of the grading technique, it does attest to its consistency, an important attribute.

The quantitative results of Experiment 2 are presented in several graphs. Figures 3.5 and 3.6 plot the number of elements correctly recorded, in the best-fit sense, as a function of exposure duration. Exposure duration is indicated in terms of number of frames on the semilogarithmic plot convenient for the presentation of the data. Even with extremely long exposure, the subjects were not able, on the average, to portray completely any of the twenty patterns. There is a great difference between individual patterns in the (5)- and (10)- sets. The results in

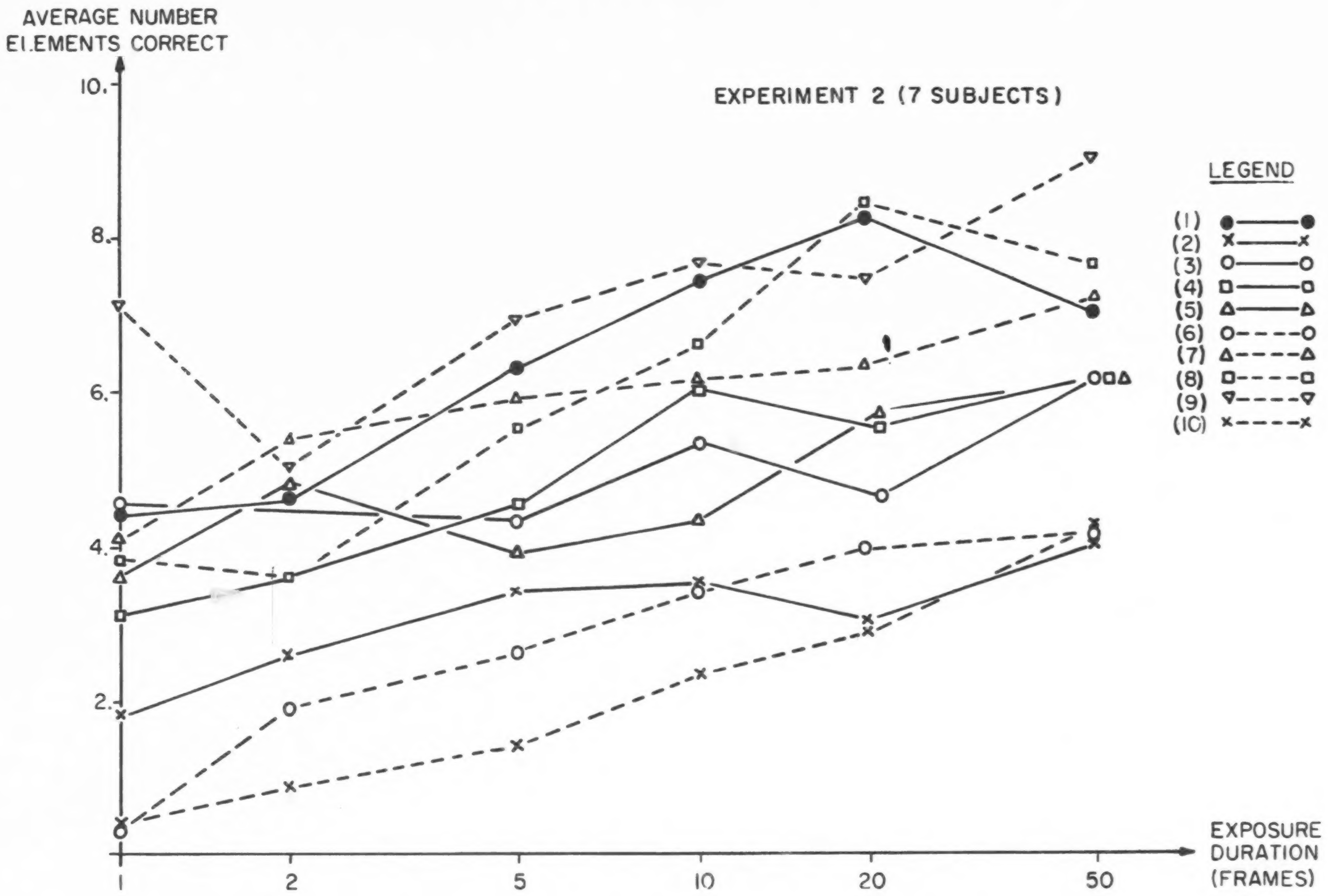

Figure 3.5. (10)-Patterns--Best-Fit Data

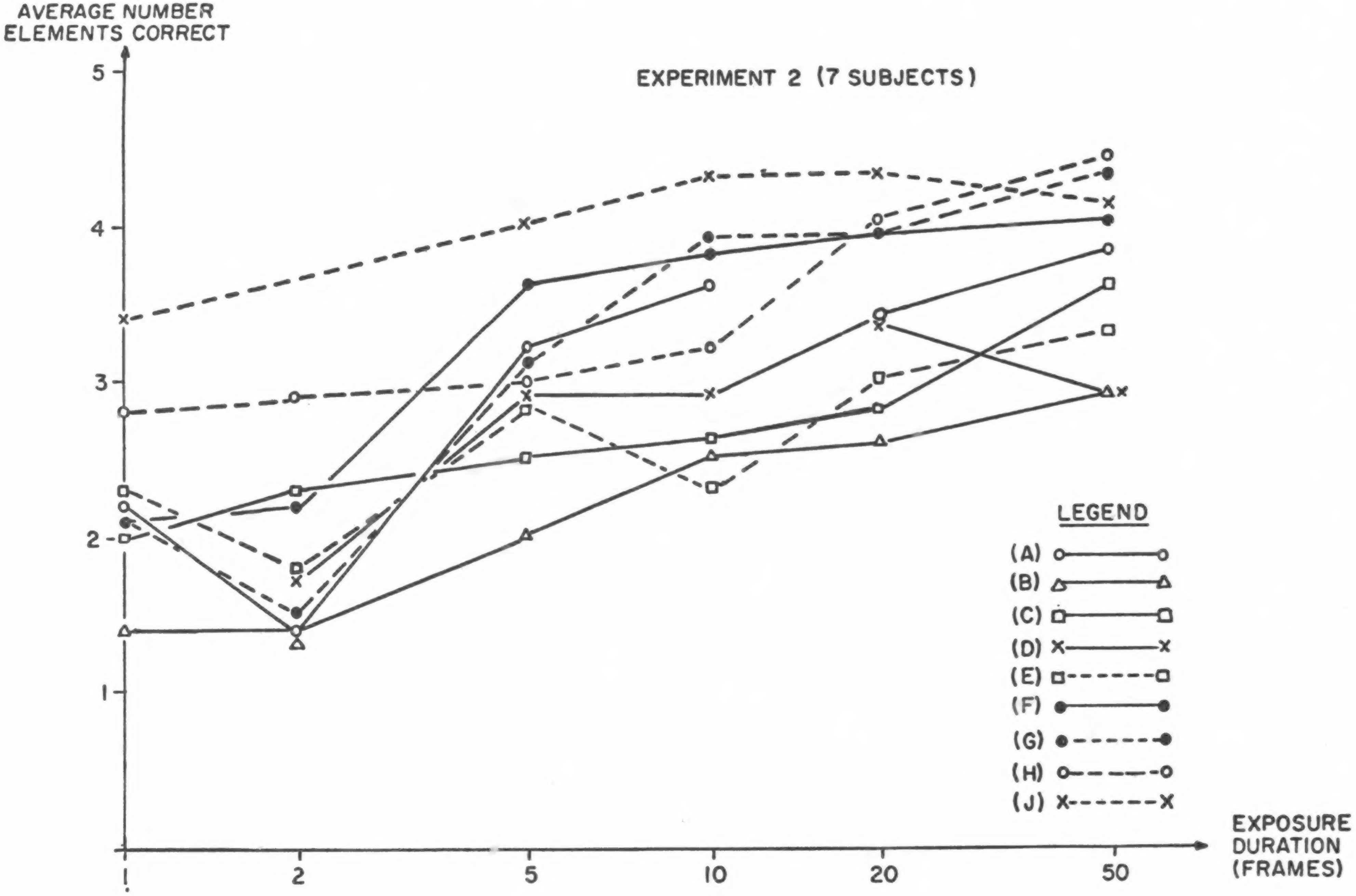

Figure 3.6. (5)-Patterns--Best-Fit Data

Figures 3.5 and 3.6 are averaged for each pattern; behavior from subject to subject is not materially different from that indicated by the average.*

Absolute registration data are not plotted for all patterns. However, Figures 3.7, 3.8, and 3.9 provide a comparison of absolute registration and best-fit data for three pairs of (10)- and (5)-patterns. The reader should note that in general the absolute registration grade (number of elements) is much lower than the best-fit grade. These three figures illustrate a fundamental point in the subjects' processing organization. For very short duration exposures (one frame) patterns that in Experiment 1 were most often regarded as structured have the greatest separation between the absolute registration and best-fit curves. Patterns most often regarded as random [(6) and (10)] have the same asymptote (for short durations) for both absolute registration and best-fit data. This general characteristic is noted throughout. It is not an unexpected result. When one is suddenly exposed to a very highly patterned exposure, the patterning aspect is far more important than the registration of the individual squares. When confronted with no obvious pattern, the subject appears to revert to a technique of measuring the coordinates of one or two of the squares (about all that can be managed for very short duration exposures). Although the results have not been plotted for other patterns, it is generally true that more random patterns (according to the classification in Experiment 1) have the smallest separation between absolute registration and best-fit asymptotes for short-duration exposures.

A few general statements can be derived from the raw data in Figures 3.5 through 3.9.

1. Almost all subjects reported a total number of squares less than or equal to the number presented.

2. An angle-shifting phenomenon was noted on some patterns with two squares forming a line to the left reported almost invariably for short exposures as forming a line to the right.

3. In general, subjects were much more adept at reporting pattern features than correct placement or registration elements within the matrix. This is especially evident in Figure 3.10.

4. The long-duration asymptote varies significantly from pattern to pattern. This asymptote is, in general, highest for structured patterns, lower for patterns over which there is some question (from Experiment 1), and much lower for random patterns. These three asymptote groupings for long exposures are based on the results of Experiment 2.

**If the reader is interested in verifying this point, he should consult the raw data for the experiment which are compiled in Appendix B.*

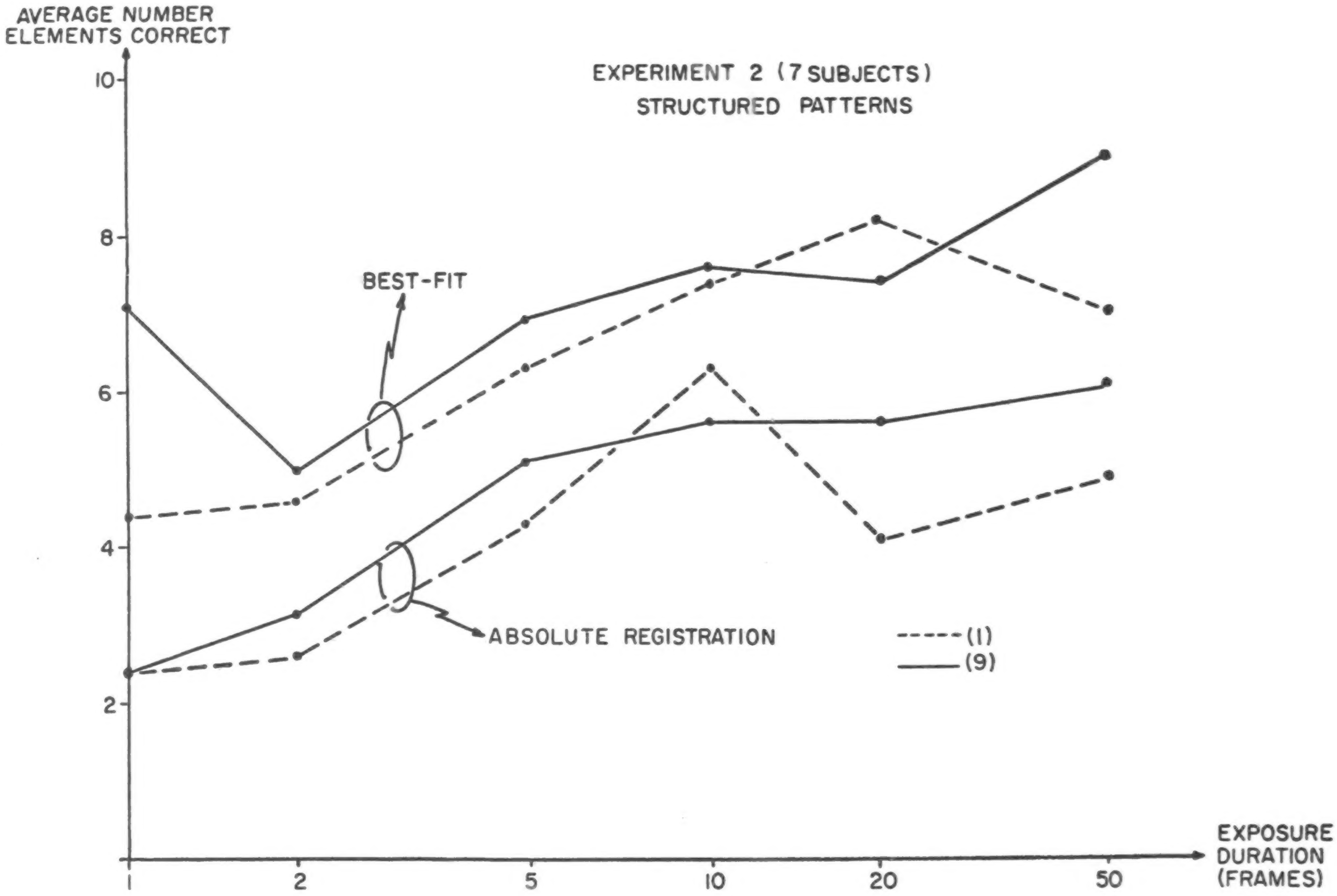

Figure 3.7. Patterns (1) and (9)--Best-Fit and Absolute Registration vs Duration

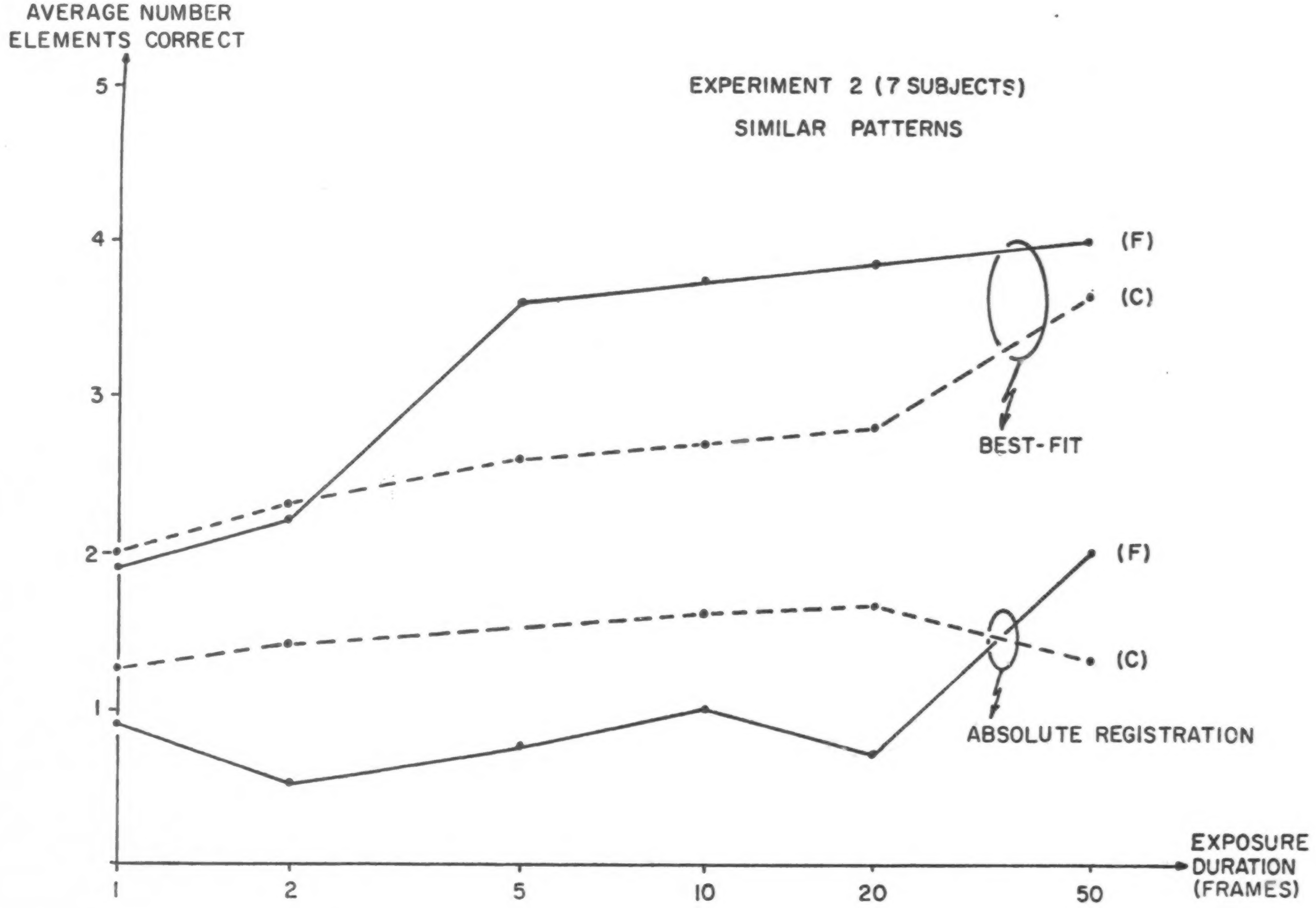

Figure 3.8. Patterns (C) and (F)--Best-Fit and Absolute Registration vs Duration

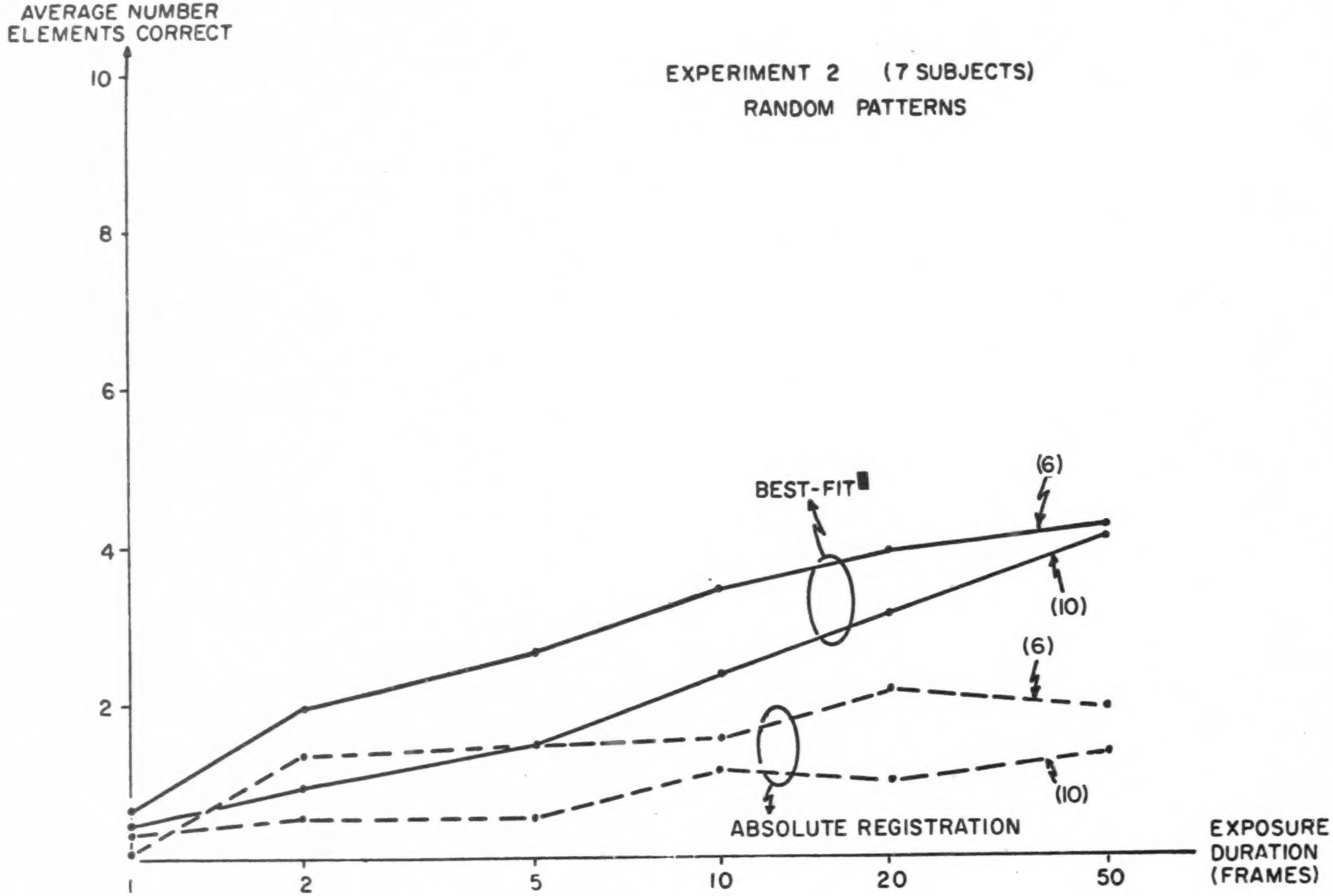

Figure 3.9. Patterns (6) and (10)--Best-Fit and Absolute Registration vs Duration

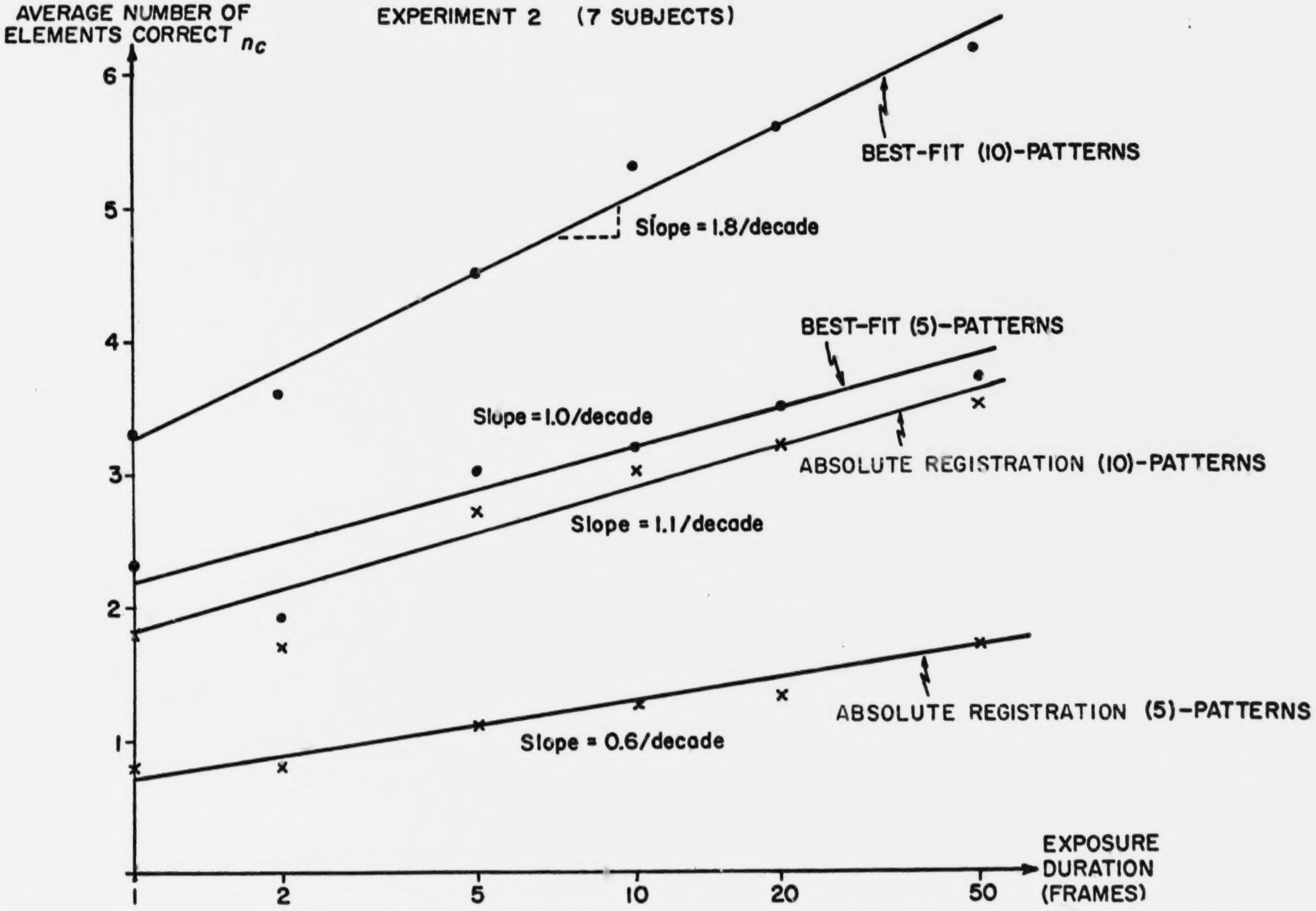

Figure 3.10. Average Best-Fit and Absolute Registration Grade vs Duration

(10)-Patterns		(5)-Patterns	
Asymptote	*Patterns*	*Asymptote*	*Patterns*
>7.0	(1), (7), (8), (9)	>3.5	(A), (F), (G), (H), (J)
5.0	(3), (4), (5)	>3.5	(B), (D), (C), (E)
3.0	(2), (6), (10)		

The high correlation between asymptote and random-structured grouping in Experiment 1 is significant.

The raw data, which were averaged over subjects and plotted for each pattern, show significant shape differences between the individual patterns. But, a word of caution is in order here. The axis involves only five squares for the (5)-patterns and ten squares for the (10)-patterns. One must consider the variance of each of the experimentally measured points to determine the degree to which the measured shapes of the individual curves are significant. In general, the variance is less than or equal to one square for each of the points in Figures 3.5 and 3.6. In a few isolated instances, probably because of imperfections in the actual projected pictures, variance reaches as high as 1.5 squares. Averaging over the seven subjects has a decided "smoothing" effect, and these variance figures indicate that some of the less significant shape variations must be taken "with a grain of salt." However, the gross features of the individual patterns, especially their high-duration and low-duration asymptotes (at these points the variances are significantly smaller), are statistically significant.

Figure 3.8 involves two patterns, (C) and (F), which are in a sense similar. Low-duration and high-duration exposure asymptotes are essentially the same for (C) and (F) with respect to both absolute registration and best match. However, the shapes of the performance curves differ appreciably between these asymptotes. In Experiment 1 (Figure 3.2), (C) was classified random by 60 percent of the subjects, and (F) was considered structured by 60 percent. This performance difference for moderate durations is strongly related to the results of the classification experiment; it is discussed in detail in section 3.4. Many patterns [(A), (C), (G), (2), (3), (7), (9), (10)] exhibit a sharp upward slope in performance between twenty and fifty frames. This improvement is attributed to premature response (before the pattern exposure is over) and a second glance and report by the subject. Although an attempt was made to discourage it, many instances of premature response were observed. This point demonstrates why the long-duration limit of the one-glance region should be taken at 3 sec (50 frames), and the performance enhancement offered by a second related glance.

What about the subjects' training level and experience? Subjects were selected only on the basis of their availability. Several practice exposures were included to assure that they understood the experiment. In all cases the author served as a subject before conducting the experiment on others. There was very little difference between his performance and that of naive subjects. Furthermore, in several of the experiments that required many exposures, performance did not improve materially with time for any subject. The same behavior was noted when the experiments were repeated with selected subjects. Thus, it is concluded that significant learning or practice effects are not manifested within the time duration of a given experiment, nor does it appear that significant learning takes place during practice runs. In either case, wide variation between subjects attributable to different learning rates was not observed.

3.4 Pattern-Recognition Organization

The major significance of Experiment 1 is that its results provide a basis for examining individual pattern-recognition performance (in a best-fit sense) in terms of pattern groupings. For instance, the fact that patterns (1), (8), and (9) were regarded as structured by all subjects prompts the question, "For these pattern groups, what common features have the best-fit grade and absolute registration grade as a function of exposure duration?" We must bear in mind, of course, that the measured variance in these experimental points precludes exhaustive examination of the fine structure of these responses (at least the average responses). However, experimental data strongly support the following summary of organizational principles.

Four typical best-fit grade-versus-duration curves can be observed in the results of Experiment 2 (see Figures 3.5 and 3.6). These are shown in Figure 3.11. Performance with random patterns increases linearly (on semilog graphs) for both the (5)- and (10)-sets with no marked deviation at any particular exposure duration. Structured patterns, on the other hand, are generally characterized by an interval of exposure durations during which there is a sharp upward increase in slope. Outside of this region, structured patterns are indistinguishable from random patterns (except for level of performance). Thus, it is concluded that the major distinction between structured and random patterns, as measured by Experiment 2, is the perception of "unity" which characterizes the structured patterns. Until this unity is perceived, there is little increase in performance with duration; after it is perceived, there is again little increase in performance because the pattern details exceed the span of immediate memory. The structured (10)-pattern elements result in a higher level of performance for short duration than for random patterns or for structured (5)-patterns because of the higher spacial density of closely related elements.* The same general statements

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**Durations of one frame are too short for eye motion to occur; thus, element density in local regions is quite important. The effects of spacial extent and eye motion are discussed further in section 5.*

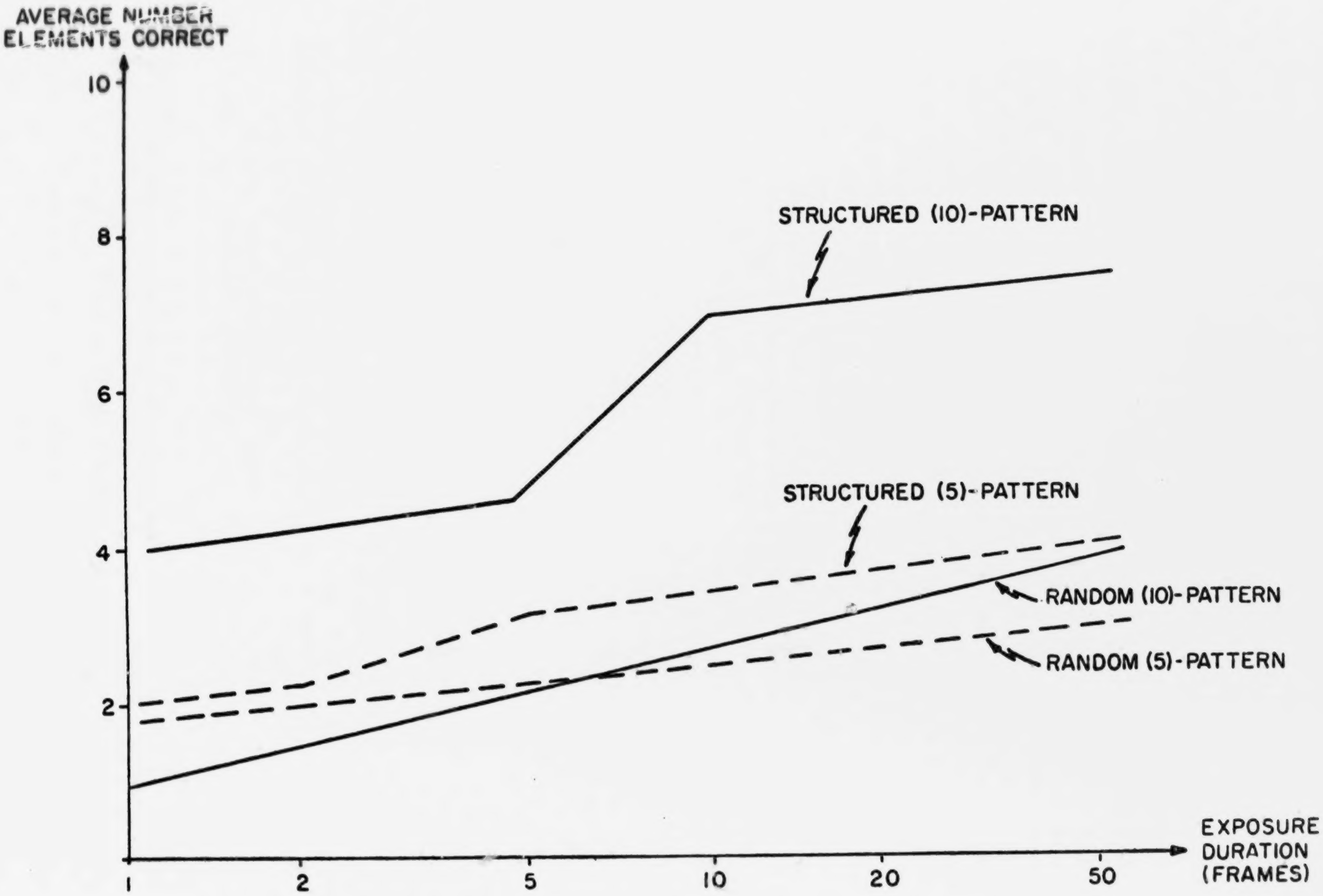


Figure 3.11. Typical Best-Fit Grade vs Duration Curves

also hold for (5)-patterns. Furthermore, the difference in performance between random and structured members of the (10)-set is greater than in the (5)-set (see Figure 3.11). This is closely related to the results of Experiment 1, which indicate generally greater difficulty in the distinction between random and structured in the (5)-set. Spacial density of elements is also lower for the (5)-set. The asymptotes in Figure 3.11 agree closely with those on page 57.

The value of exposure duration for which the structured patterns begin to exhibit sharp upward slope depends upon the pattern. For some patterns it apparently occurs before the lower duration bound on the one-glance region (one frame). The performance curves for patterns (H) and (J) (see Figure 3.6) demonstrate that this critical duration is a definite function of pattern size, with larger patterns exhibiting greater latency.* In general, the rise occurs between 125 msec and 300 msec (two and five frames) for (5)-patterns, and between 125 msec and 625 msec (two and ten frames) for (10)-patterns.#

To demonstrate these principles, pattern data are presented with respect to random-structured groupings in Figure 3.12 for (5)-patterns and Figure 3.14 for (10)-patterns. The structured (5)-patterns selected are (A) (75 percent), (F) (60 percent), and (G) (85 percent); all exhibit a performance increase between two and five frames. The random (5)-patterns are (B) (75 percent), (C) (60 percent), and (D) (70 percent). Because the shapes and asymptotes of these curves are quite similar, they have been averaged for convenience. Similarly, in Figure 3.13 the structured set of (10)-patterns [(1) (100 percent), (7) (80 percent), and (8) (100 percent)] was selected; the random (10)-patterns chosen are (2) (100 percent), (6) (70 percent), and (10) (95 percent). These results hold for all structured and random patterns of both (5)- and (10)-sets, which strongly suggests the organization of response illustrated in Figure 3.11.

Julesz (1) has demonstrated that the perception of form in binocular displays that appear to be random can take 90 sec or more; until this time the pattern appears completely random.† If subjects were asked to reproduce these patterns after shorter duration exposures, they would presumably have to resort to reporting the element coordinates. Once the essential unity was perceived, one would expect performance to rise sharply and then level off because pattern details would far exceed span of memory. The results of Experiment 2 illustrate this same qualitative behavior at much shorter times largely due to the much smaller matrix ensemble (two orders of magnitude in each dimension).

**Patterns (H) and (J) essentially differ in sizes only, (J) being a smaller, inverted version of (H).*

#It is shown in section 5 that voluntary eye motion does not occur until at least 125 msec after *the onset of the stimulus flash.*

†This effect also occurs for monocular patterns.

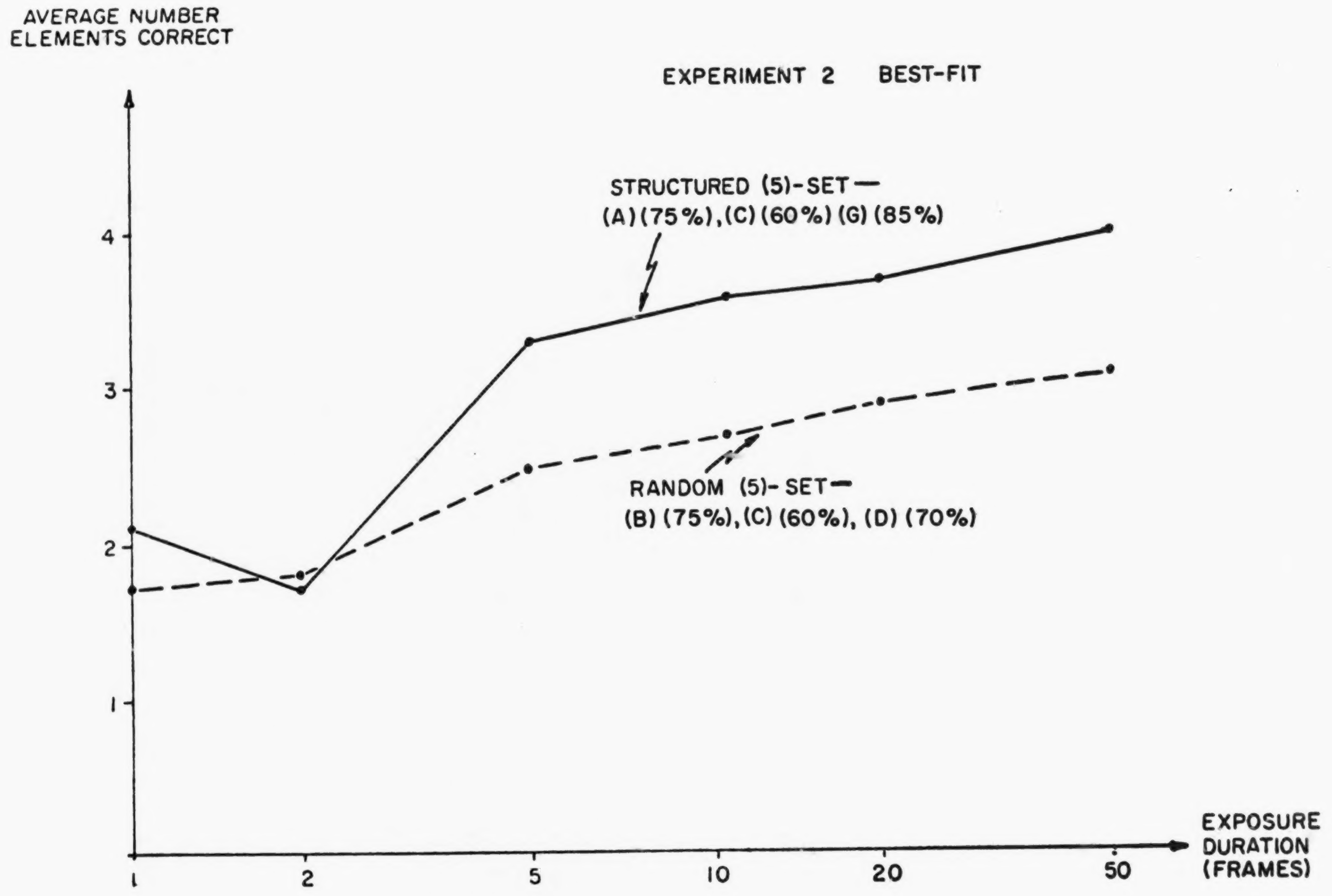


Figure 3.12. Structured and Random (5)-Sets--Performance vs Duration

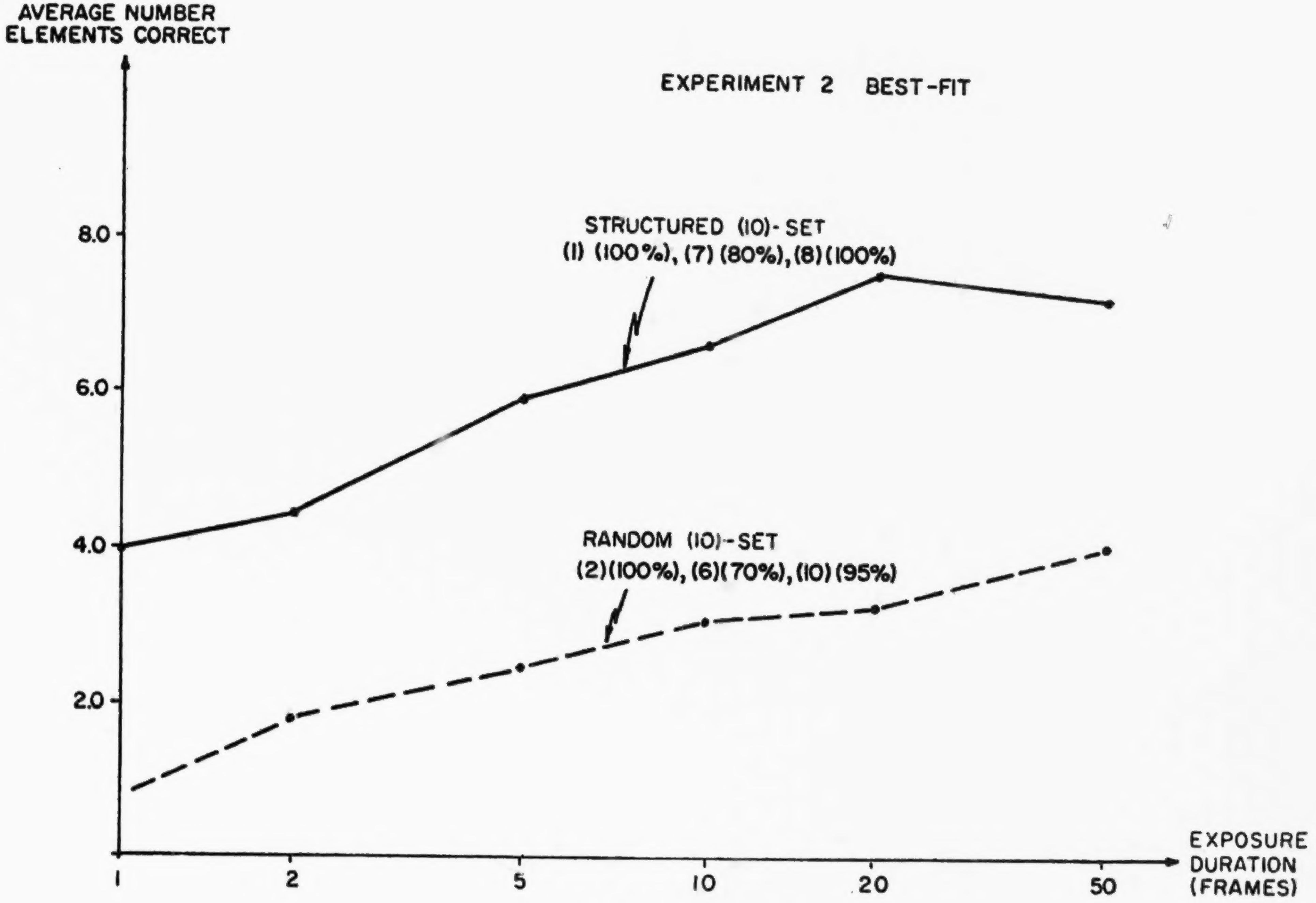


Figure 3.13. Structured and Random (10)-Sets--Performance vs Duration

3.5 Letter Report from a Spacially Distributed Array—Some Contrasts

We have examined performance in a pattern-recognition experiment requiring total report (pattern reproduction) and have deduced several organizational principles for performance prediction. In dealing with pattern sources, we are generally unable to express quantitatively the way in which information is shared between the elements. In general, however, the various elements of the spacial array which forms the pattern are related. In this section an experiment involving total report from unrelated elements in a spacial array is discussed.

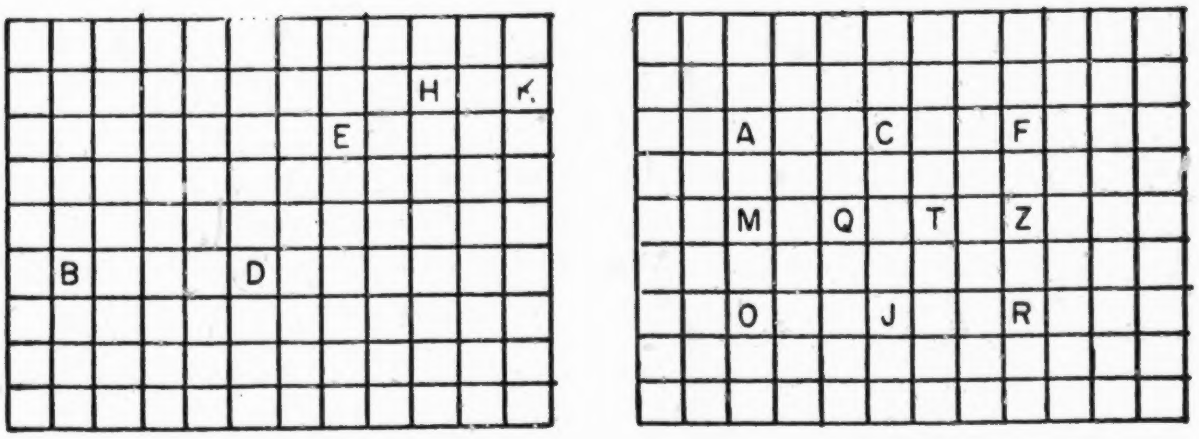
Experiment 3

Six subjects were exposed to forty-two test patterns for durations of 1, 2, 5, 10, 20, and 50 frames of a motion picture display. The timing of each display was as shown in Figure 3.3. The stimulus material consisted of five or ten English letters arranged within the 9 × 12 matrix in the element positions of the patterns (H), (J), (B), (1), (2), (6), and (8). Each pattern was exposed six times, once for each duration. In addition, several practice patterns were exposed. The patterns were arranged in a random order both with respect to duration and spacial array (patterns). The letters were chosen such that each was equiprobable (zero-gram English). The subjects were instructed to write along a horizontal line as many of these letters from each exposure as possible without respect to position or order in the array. Figure 3.14 illustrates a typical stimulus for the (B)-array and (1)-array. The letter arrays were projected to subtend angles of approximately 9 deg to the subjects. The light level was the same as in Experiment 2.

Experiment 3A

Three of the six subjects were tested with six redundant exposures of pattern material; pattern (J) was exposed for 2 and 20 frames, (1) for 5 and 50 frames, and (6) exposed for 10 and 20 frames. Exposures were mised among the 42 exposures of Experiment 3. The six patterns in Experiment 3A contained different letters (chosen at random) from those in the corresponding exposures in Experiment 3.

Experiment 3A was designed to determine the extent to which the results of Experiment 3 depended upon the actual letter combinations in the spacial array. Figure 3.15 compares the letter report from the same spacial array for different letters. There is little difference between individual subjects and virtually no difference in the total number of letters reported by the three subjects together, which indicates that the differences between letter arrays are well within experimental precision.



B-ARRAY I-ARRAY

Figure 3.14. Sample Letter Arrays--Experiment 3

	EXPERIMENT 3 LETTER GROUP I					EXPERIMENT 3A LETTER GROUP 2		
SUBJECT →	①	②	③	TOTALS		①	②	③
J-2	3	1	2	6	8	3	3	2
J-20	5	3	5	13	15	5	5	5
(1) - 5	3	3	3	9	9	4	2	3
(1) -50	9	5	4	18	18	7	5	6
(6) -10	5	3	3	11	10	4	3	3
(8) - 20	5	4	4	13	13	5	4	4
PATTERN DURATION								

Figure 3.15. Letter-Report Dependence--Experiment 3A

The average number of letters correctly reported for the four-letter patterns [(B), (H), (J)] and ten-letter patterns [(1), (2), (6), (8)] are shown in Figure 3.16. For short durations (one and two frames) the letter report is virtually independent of the number of letters present. The two curves diverge by about one letter from two- to twenty-frame exposures, indicating that increasing the source rate does not increase performance but, in fact, results in poorer performance. The higher source rate (ten letters) ultimately results in an average of six correct letters reported, while the five-letter patterns are completely reported (virtually) at the 50-frame exposures (3 sec). Almost all the letters reported were correctly reported; about 2.5 percent were incorrect. The most common incorrect reports involved confusion between "U" and "V."

The major difference between Experiments 3 and 3A and other short-duration-exposure letter-report experiments is the uncertainty in the letter positions (and number of letters). Miller, Brunner, and Postman (2), in examining total report from eight-letter sequences of zero-order English, measured results which follow the five-letter pattern curve from Figure 3.16 remarkably well from one to ten frames. Sperling (3), on the other hand, finds that subjects can report 4.5 to 6 letters regardless of exposure durations from 15 to 500 msec from 3 × 3 letter arrays. These results are difficult to reconcile at this point; uncertainty in letter position is undoubtedly significant as is the size difference (angle subtended) in the patterns. Generally, these points are explored in greater detail in section 5.1.

To consider the contrasts between letter report and pattern recognition, we shall examine the letter report results for the various spacial arrays (patterns). Figures 3.17 and 3.18 show the letter report data by pattern. The long-duration asymptote is independent of pattern, with about six letters reported from the (10)-patterns and five letters from the (5)-patterns. For short-duration exposures there is very little difference between five-letter and ten-letter presentations, but performance begins to improve earlier (two frames) for the (5)-patterns than the (10)-patterns (ten frames). This effect, which is related to the problem of context and eye motion discussed in section 5.4, accounts for the poorer average performance of the ten-letter displays for exposures from two to twenty frames.

Two other significant facts should be pointed out here. First, the span of memory compression offered by the relation between the elements of a pattern as opposed to the array of independent English letters is exemplified by comparison of Figure 3.17 or 3.18 with 3.5 or 3.6. Six items (when the items are English letters) can be reported from a (10)-pattern array after a long exposure. For related pattern elements the number of elements varies from 3 to 7 depending upon the detailed relationship between the pattern elements. Of course,

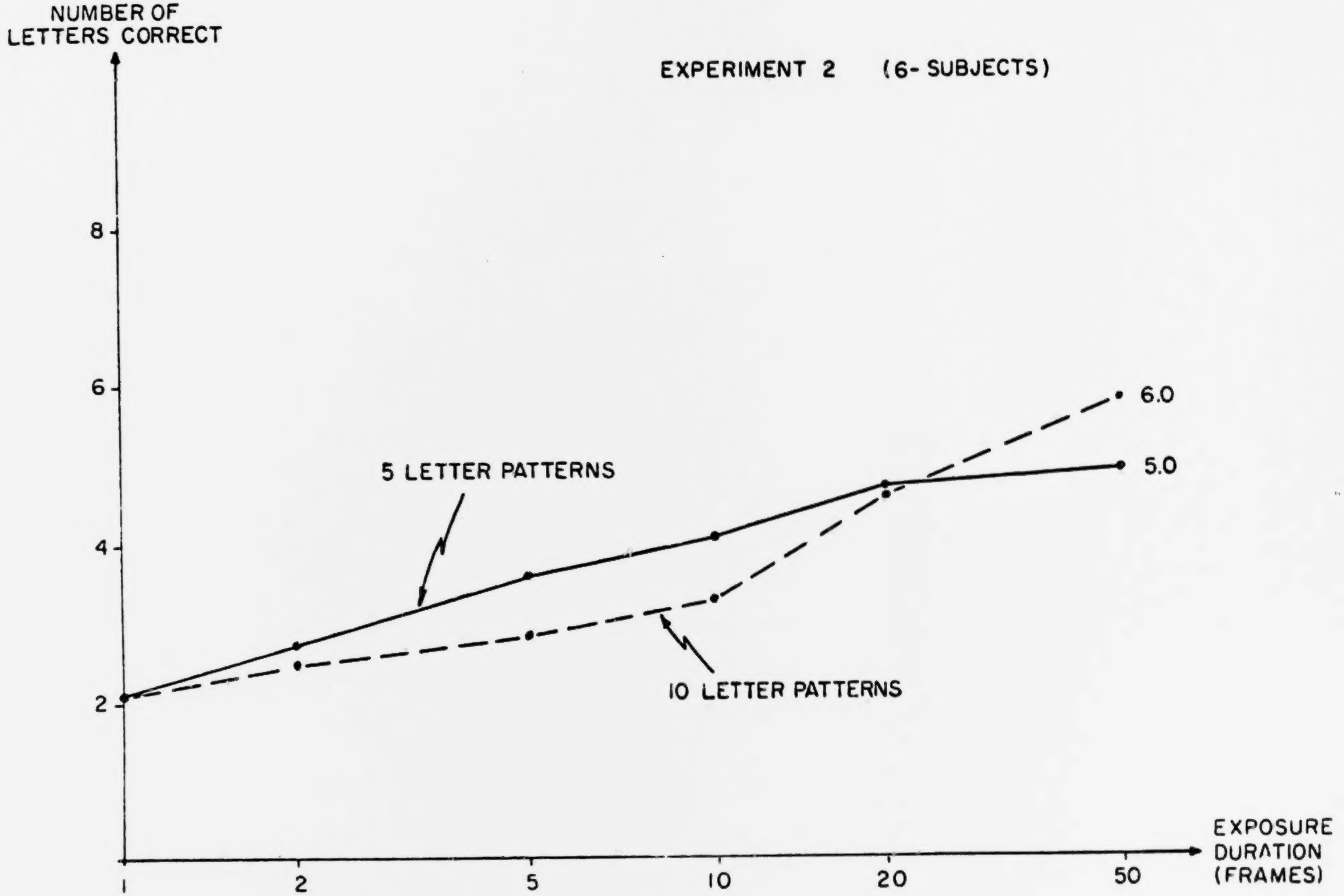


Figure 3.16. Number of Letters Correct vs Exposure Duration

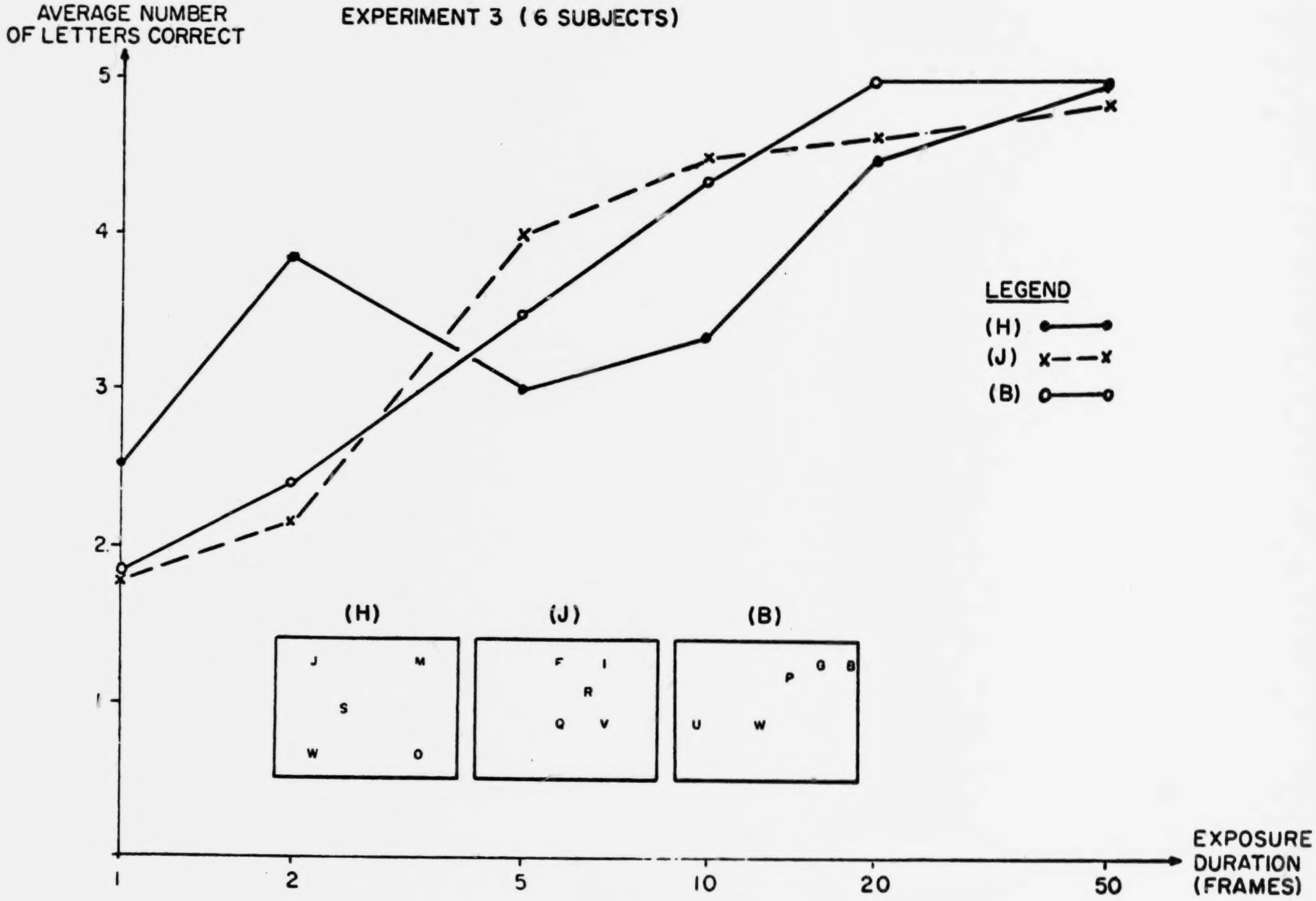


Figure 3.17. Letter Report vs Duration--Five-Letter Patterns

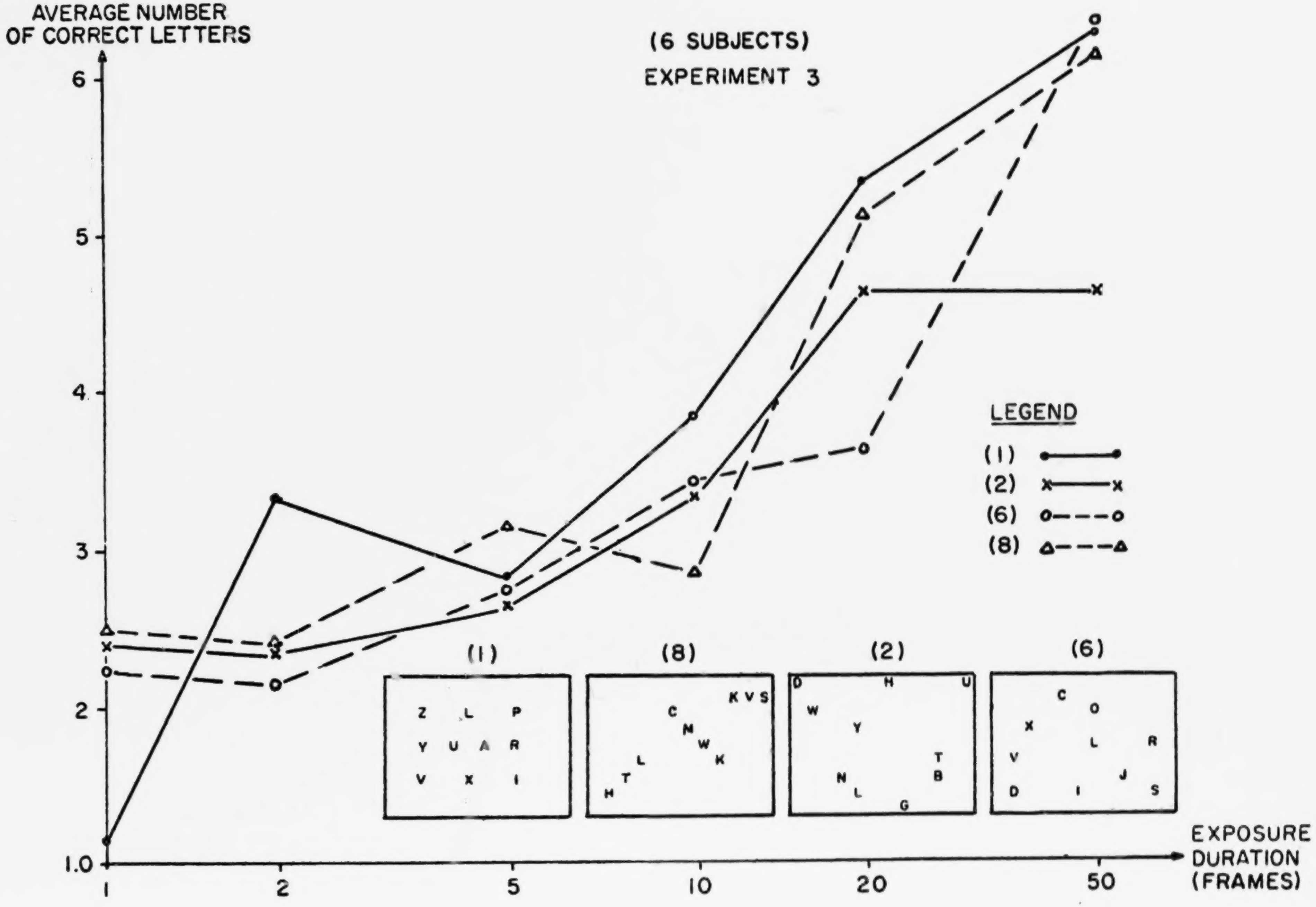


Figure 3.18. *Letter Report vs Duration--Ten-Letter Patterns*

the two situations are not particularly related except in the spacial distribution of elements. Second, there is very little difference in performance as a function of the shape of the spacial array (in comparison to the performance differences between the given patterns in Experiment 2), but these significant differences in performance as a function of the number of elements in the array.

REFERENCES

1. B. Julesz. "Binocular Depth Perception of Computer Generated Patterns," *BSTJ*, 39(5):1125-62 (1960).

2. G. A. Miller, J. S. Brunner, and L. Postman. "Familiarity of Letter Sequences and Tachistoscopic Identification," *J. Gen. Psychol.*, 50:129-31 (1954).

3. G. Sperling. "The Information Available in Brief Visual Presentations," *Psychological Monograph*, 498 (1960).

4. PATTERN RECOGNITION IN SHORT-TERM MEMORY

The experiments described in Section 3 involve information transmission measured through the subject's total report. It has been pointed out that the major limitation of psychophysical measurements involving total report is the apparent saturation of the span of immediate memory on relatively short-duration exposures. For instance, in only a very few cases of the patterns described in Experiment 2 were subjects able to relate correctly (in the best-fit sense) more than about six of the ten squares forming each of the (10)-patterns. Subjective reports indicate that subjects saw many more things than they were able to report. Thus, we conclude that there is much more information available in short-duration visual exposures than can be recalled in total-report experiments.

The total report of information perceived through short glances is a very artificial means of information utilization. In the normal visual situation, information perceived in short glances is not reported at each glance; rather, it is transferred from glance to glance in a way that provides a net information intake very much higher than that predicted on the basis of short-duration visual exposures such as those measured in Section 3.

The saturation of immediate memory requires further discussion. In Section 2 it was noted that all psychophysical experiments involve two mechanisms--the stimulated modality and the response mechanism. It does not stretch the imagination (or the great bulk of physically measured data), to assume that information cannot be transferred directly from visual to speech output without processing in the higher brain centers. The span of immediate memory limitation may not be imposed by the information available in vision, but rather by the information that can be conveniently transferred in one "clump" from the visual modality to speech or to the motor system for written reports. To avoid the psychophysical bind, or bottleneck, apparently caused by the higher brain centers, information available before the brain has been sampled in a series of visual modality experiments. The basic premise of this experimentation is that if we require only a minimal amount of information to be transferred to the response modality, we can infer a great deal more about the information that must have been available to make the single or very low-order decision actually reported. Experiments of this type have indicated through the higher information rate figures they report that very important, high-capacity buffer storage exists in the visual system (1, 2). Furthermore, these experiments indicate that this buffer storage is a very important mechanism in the reception of visual information.

In this section problems of pattern recognition (or spacial relations) in the short-term memory--which, in general, are not treated in the literature--are considered. A sampling technique for the measurement of short-term memory effects, especially as they relate to pattern recognition, has been devised, and a sampling experiment intended to point out the significant differences between pattern recognition involving short-term memory and pattern recognition involving total report has been performed. This experiment is described and pertinent literature on short-term memory effects in vision is discussed.

4.1 Short-Term Memory in Vision

Though many psychophysical experiments on vision require partial report by the subjects (3, 4, 5), the first comprehensive experiments regarding sampling of the information available in short-term visual presentations were performed by Sperling (1), and by Averbach and Coriell (6). In addition, Averbach and Sperling have presented a comprehensive measurement of the role of short-term memory in vision (2). These researchers have demonstrated that the visual process involves a high-capacity buffer storage with essentially instantaneous information read-in and relatively slow information read-out. This buffer storage is susceptible to erasure and confusion and has a very high capacity compared with the normal amount of information one measures in visual-transmission experiments. For instance, the buffer storage has been shown to have a capacity of at least seventy information bits, compared with five to ten bits ordinarily transmitted per exposure by total report. The decay and erasure characteristics of this phenomenon have been carefully investigated by Averbach and Sperling.

It is the author's contention that the major contribution of Averbach and Sperling's work does not lie in their excellent measurements of the role of short-term memory in the visual process. Rather, they have demonstrated a technique for comprehensive psychophysical measurements which do not suffer from the span of immediate memory limitations ordinarily encountered in such experiments. Further, their technique permits inferences about the visual information available before the higher brain centers. The significance of measurements on visual information availability early in the visual information-processing chain is almost unlimited. In television transmission problems one is intimately concerned with the question of ability to transfer information from frame to frame. To investigate what kind of information can be carried from one to another short-term exposure, one must, of course, have techniques for measurement that do not involve total report. The really interesting (and most common) phenomena in vision do not involve total report; but it is safe to assume that these visual processes, which are responsible for the large intake of visual information in normal operation, involve the transfer of information from short-term memory between successive exposures to extremely complex visual stimuli. Furthermore, it is most probable that such visual information processing must be under strong control of the higher brain centers. Work on the octopus (7) and, to a certain extent, on the human (8) has indicated that certain visual recognition processes involve efferent information from the higher brain centers. Presumably, this information, which enters retinal ganglia, influences the mechanism of transfer in the short-term visual memory.

It is interesting to note that despite their detailed quantitative measurements, Averbach and Sperling still admit that short-term memory in vision may not be as distinct from common afterimage phenomena as one might suspect. Thus, the role of visual afterimages, generally associated with short-duration displays, remains essentially unresolved with respect to normal processes. Common afterimage phenomena may merely be the manifestation of the truncation of sequential visual stimuli--that is, they may be the manifestation of the eye's "surprise" at its inability to transfer information to another glance.

4.2 A Sampling Technique for the Measurement of Short-Term Memory Effects

The results of Experiment 2 clearly demonstrate the saturation of the span of immediate memory in pattern recognition. To surmount this difficulty in assessing the information available earlier in the visual processing chain in short-duration pattern exposures, an approximate and to a certain extent arbitrary sampling technique has been devised for use in connection with pattern exposures identical to those used in Experiment 2. Its choice is based upon two major considerations.

1. It is to be used in a pattern-recognition experiment aimed at emphasizing the differences between total report and partial report information transmission.

2. It is to be consistent with the best-fit grading technique described in Section 3.

A pattern (the test pattern) is exposed to the subject for some duration T. After d frames of white field, a pair of possible pattern elements are shown (see Figure 4.1). The subject is asked to decide whether this pair was an exact pair from the pattern. To implement such a procedure satisfactorily, one half of the pairs is taken exactly from the original pattern; and one half differs in only a single position of one of the two elements in such a way that this pair does not form another pair (if possible). The sample pairs for a (5)-pattern, which conform to this definition, are shown in Figure 4.2.

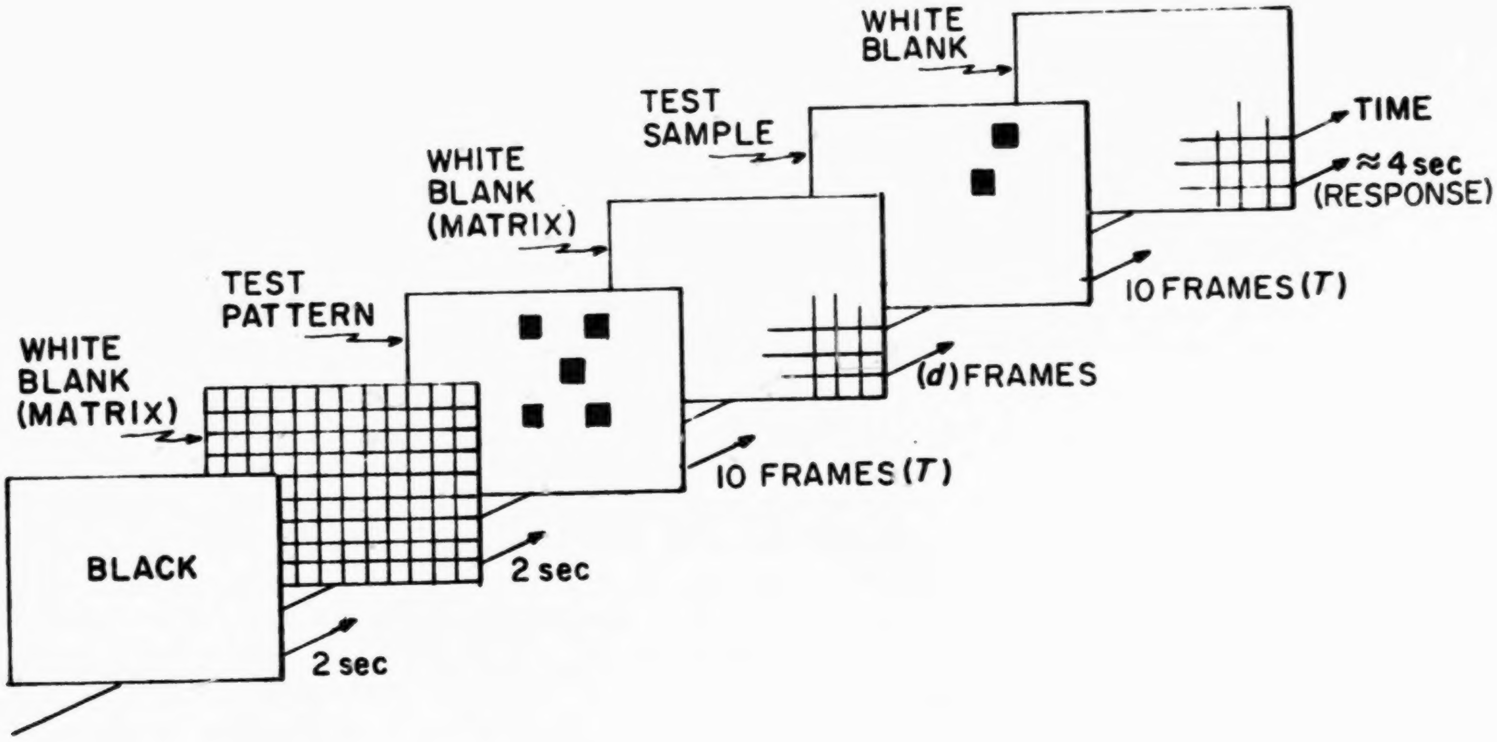

WHITE BLANK
TEST SAMPLE
WHITE BLANK (MATRIX)
TEST PATTERN
WHITE BLANK (MATRIX)
BLACK
TIME
≈ 4 sec (RESPONSE)
10 FRAMES (T)
(d) FRAMES
10 FRAMES (T)
2 sec
2 sec

Figure 4.1. *Typical Exposure Sequence--Experiment 4*

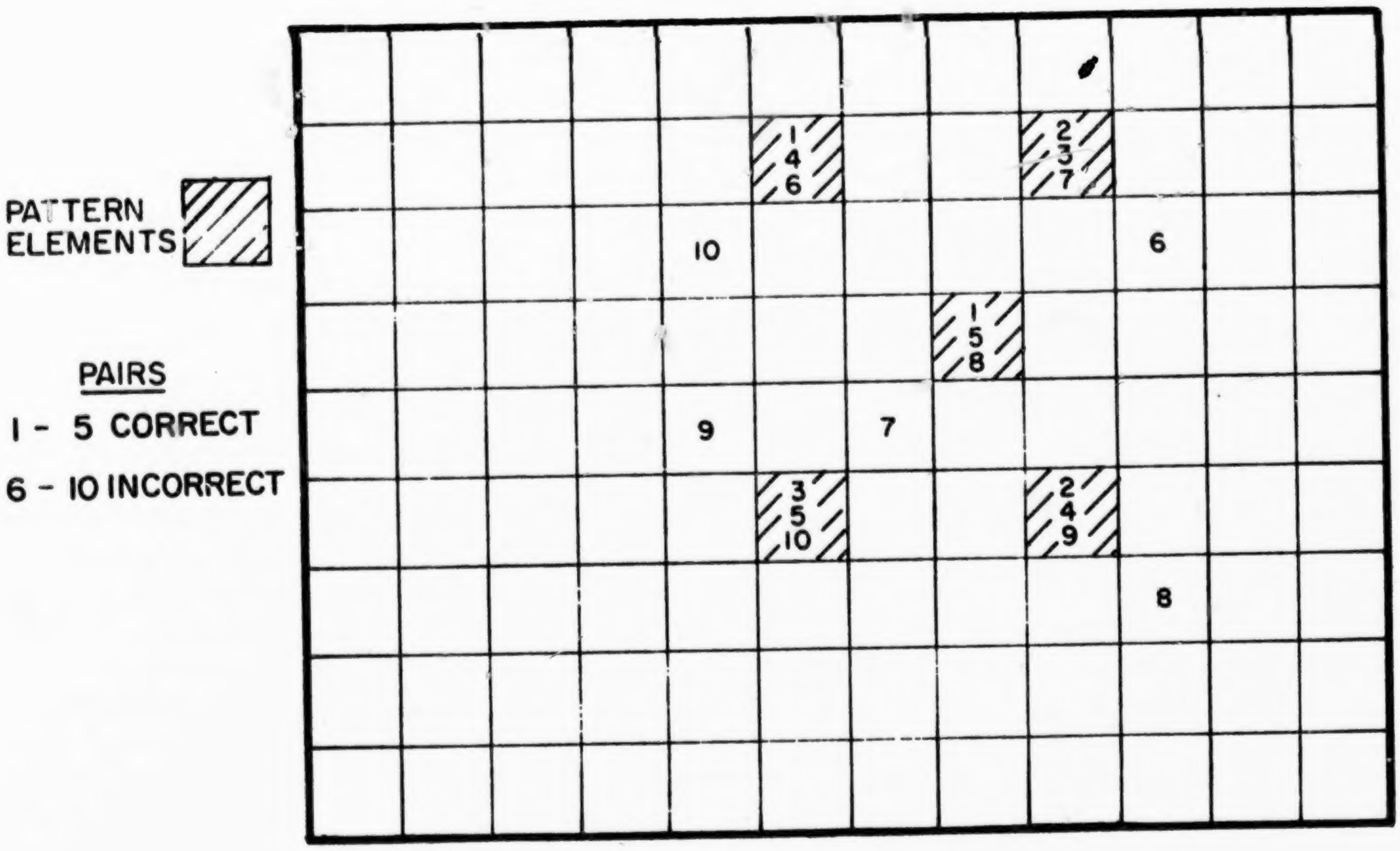

PATTERN ELEMENTS
PAIRS
1 - 5 CORRECT
6 - 10 INCORRECT
1 4 6
2 3 7
10
6
1 5 8
9
7
3 5 10
2 4 9
8

Figure 4.2. *The Ten Sample Pairs for Pattern (J)*

When the subject is shown a pattern and later asked to make a forced choice as to whether a pair of elements subsequently exposed was part of the pattern, guessing becomes a significant response artifact. The standard guessing correction factor for a two-alternative forced choice must be applied to the subject's response.

$$\% \text{ Correct} = \frac{\text{Number Correct - Number Wrong}}{\text{Total Number Shown}} \qquad (4.1)$$

Once the experiment has been performed, we wish so to relate its results to the original pattern that we are able to infer from the subject's performance in the identification of possible pattern pairs how well he must have related (in the best-fit sense) the various elements of the pattern itself. In other words, we want indirectly to measure the information that must be available on the average for the subject to distinguish correctly the pairs of pattern elements on subsequent presentation.

For a pattern of n elements, the number of pairs (n_p), is given by Equation (4.2).

$$n_p = \frac{n!}{(n - 2)!\ 2!} \qquad (4.2)$$

If the subject were able to respond correctly to a given percentage of these pairs, one could relate the percentage of pairs correctly perceived to the number of elements that must be correctly related in the pattern by the subject. The relationship between S_c, the percentage of sample pairs correctly reported, and n_c, the number of elements of the pattern correctly related, is given by Equation (4.3).

$$S_c = \frac{200}{n(n - 1)} \sum_{k = 1}^{n_c - 1} k \qquad (4.3)$$

where S_c = the percentage of samples correctly reported, n = the number of squares in the pattern, and n_c the number of squares that must have been correctly related by the subject to achieve the level of performance indicated by S_c. Equation (4.3) is plotted in Figure 4.3 for $n = 5$ and $n = 10$.

For best results, it is apparent that all possible sample pairs from a given pattern should be used. However, this is not convenient for large n. From Equation (4.2) we see that

$n = 5 \quad n_p = 10$
$n = 6 \quad n_p = 15$
$n = 10 \quad n_p = 45$
$n = 15 \quad n_p = 105$

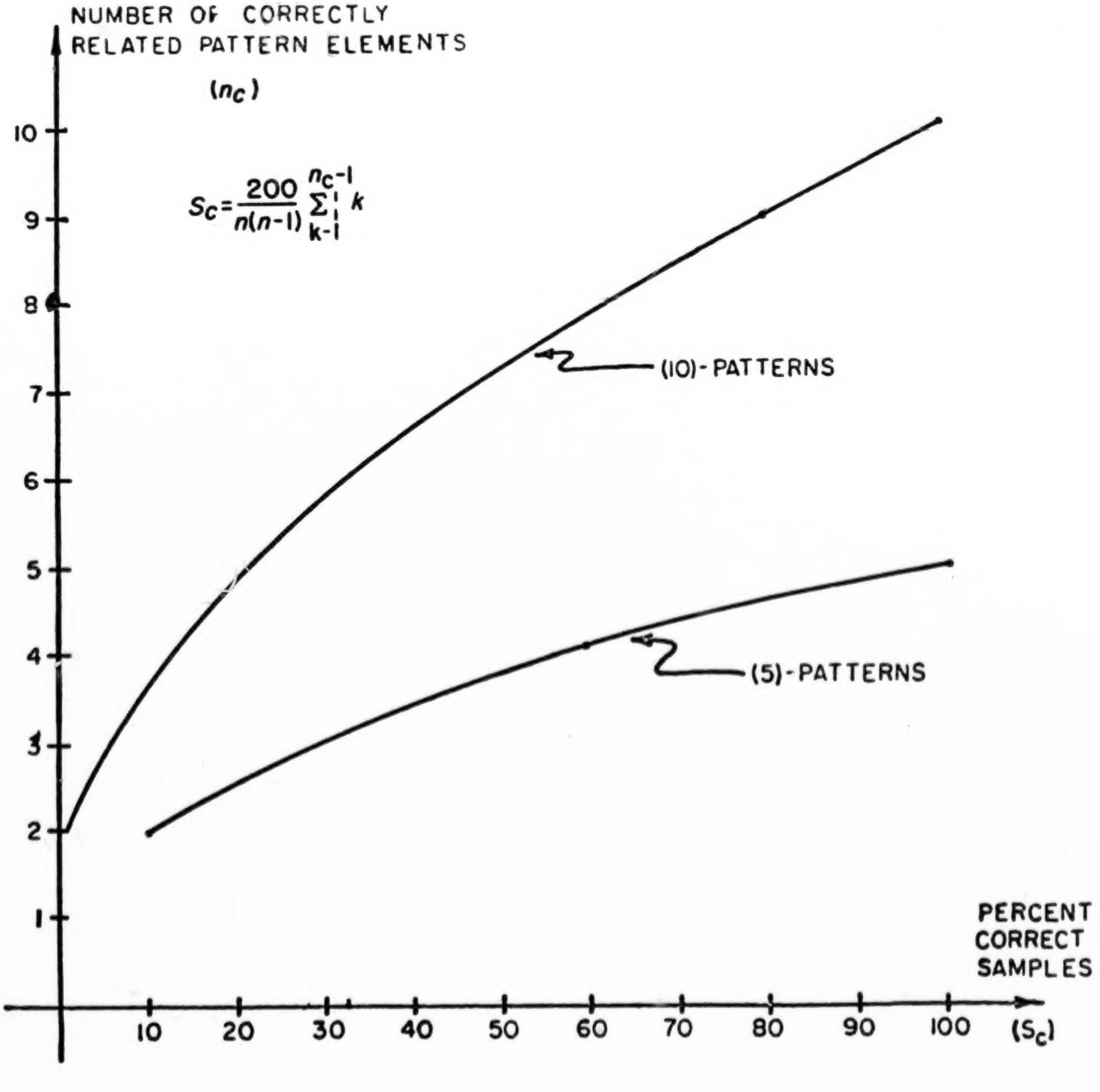


Figure 4.3. S_C *vs* n_C *for (5)- and (10)-Patterns*

To eliminate the possibility of learning (the transferral of information between subsequent exposures of the same pattern), many different patterns must be interlaced in any given experimental sequence. Thus, not only is the number of possible pairs large, but also the number of exposures that must be used to avoid undesirable effects is even larger.

In using this sampling measurement on (10)-patterns, where there are 45 possible element pairs, some further approximations are required. Instead of testing all element pairs, only ten are selected. These are chosen such that each pattern element is represented in at least two pairs (generally one correct pair and one incorrect pair). Thus, only about 22 percent of the possible pairs are tested.

4.3 Sampling Experiment

A comprehensive sampling experiment (Experiment 4) was conducted with seven of the twenty patterns used in Experiment 2.

Experiment 4

Three subjects were tested with a sampling of pattern pairs from seven of the patterns used in Epxeriment 2. Ten sample-pair exposures (five correct and five incorrect) were used on each pattern for each delay between pattern and sample. The experimental sequence shown in Figure 4.1 was used for each exposure. Both the pattern and pattern sample pairs were exposed for ten frames (≈ 625 msec). The patterns (B), (J), (6), and (8) were tested at delays of 1, 2, 5, 10, and 20 frames; patterns (F), (3), and (10) were tested only at 1, 10, and 20 frames of delay. Each subject was instructed as follows after a few sample exposures were shown: "In the four-second period following each pattern pair, you are to indicate verbally whether that pattern pair was identical to a pair of elements in the pattern shown previously. Remember, every pattern pair has one element that is identical to an element in the pattern; the second element, in general, is not far removed from a correct position. I (the experimenter) will record your answers as they are given." Three hundred exposures, as shown in Figure 4.1, were required to provide ten samples at each delay for every pattern. The running time of the movie was fifty minutes including a five-min break at the halfway point. The 300 exposures were in a pseudorandom order with respect to pattern and delay. The subjects were seated 9 ft from the screen such that the patterns subtended angles of approximately 10 deg to the subject. Experimental conditions were identical to those in Experiments 2, 3, and 3A.

Before this technique was implemented in movie form for complete testing, several pilot films were made to determine the most appropriate exposure parameters. The results indicated that performance (percent pairs correct versus delay) does not consistently rise above the guessing level (50 percent) until both the pattern and pattern sample pair are exposed for at least five frames each. One subject (the author) was able to achieve scores of 60 to 70 percent for two frames of pattern and sample exposure, but only for zero to one frame of delay. There are several reasons for these results. First, it is impossible for the subject even to "see" the entire pattern for one- or two-frame exposures; and, because the two elements from the sample often come from different parts of the pattern, the result is not unexpected. Furthermore, even though one- or two-frame exposures in Experiment 2 result in best-fit grades of up to four elements (see Figures 3.5 and 3.6), these elements are always reported from a local region of the pattern and the poor results indicated from the preliminary testing are not inconsistent with Experiment 2. Second, the few instances of better performance are most probably due to the subject's detection of apparent motion (9, 10). To all practical purposes the detection of apparent motion is performed well by peripheral vision; thus eye movement or scanning would not be a significant factor. When two still pictures are sequentially displayed with a small delay between them, the subject recognizes that they are different (if they are) by sensing that something has "moved." This effect is discussed at length in connection with the results of Experiment 4.

When a plain white background was used during the delay interval, as opposed to the blank pattern matrix, poorer performance was noted. In effect, the absence of a continuing position reference during the delay interval forces the subject to retain absolute registration data to avoid reorientation when the sample pair (and pattern matrix) reappear. Thus, it was decided to use the blank matrix for background both in the delay interval and report interval.

Figure 4.4 depicts the average number of correctly related pattern elements (n_c) as a function of delay between pattern exposure and sample exposure for the (5)-patterns (B), (F), and (J). The grade n_c is computed from Equation (4.3) using the value of S_c based on the average number of samples correctly recognized by three subjects. The guessing correction factor given by Equation (4.1) also has been applied to the experimental data.* The same results are plotted in Figure 4.5 for the (10)-patterns (3), (6), (8), and (10). The $n_c = 0$ line is the locus of points for which the number of correctly recognized samples is below the chance level (50 percent).

**The experimental data are tabulated in Appendix B, Table B-5.*

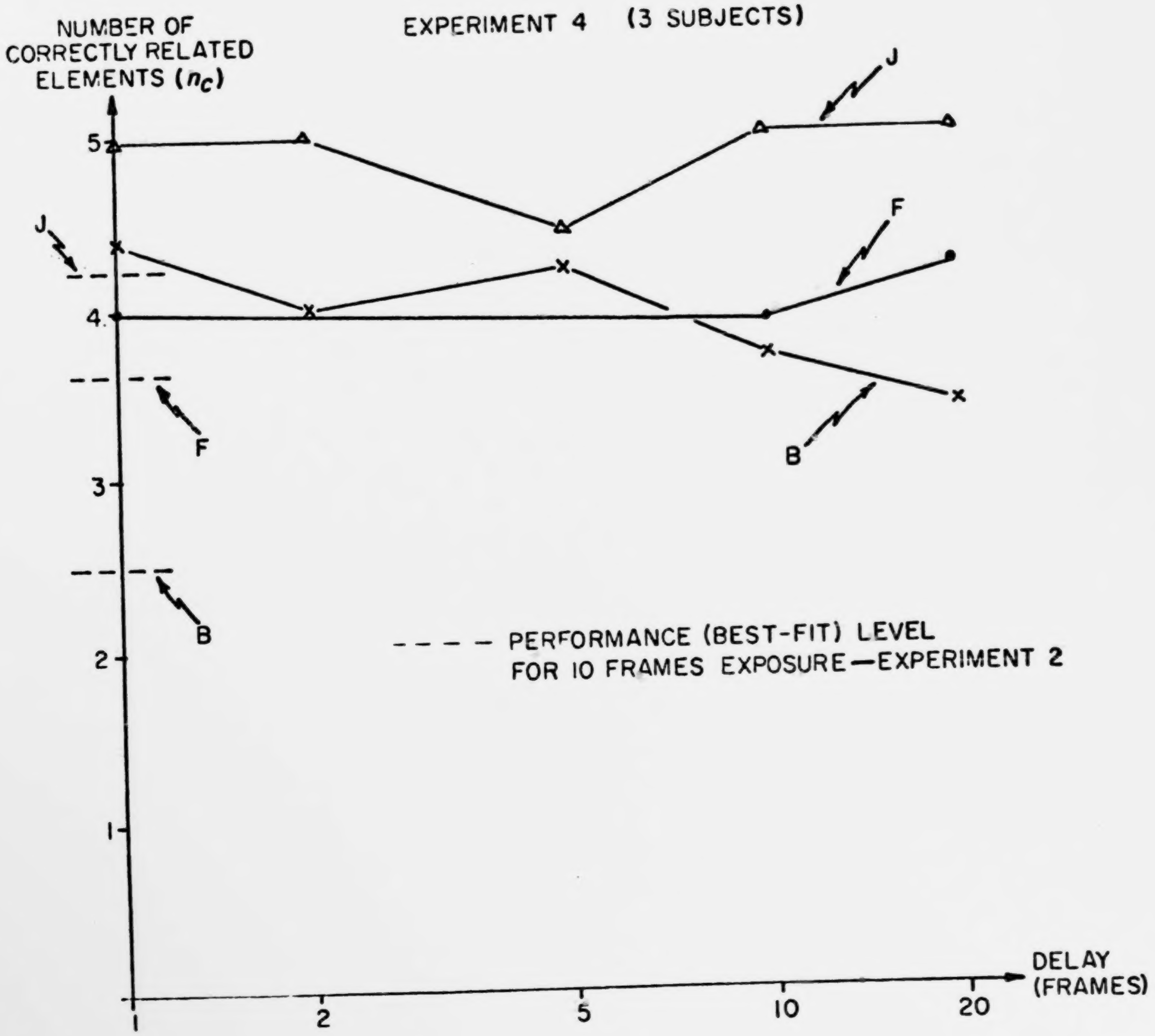


Figure 4.4. n_c *vs Delay--Sampling Experiment*

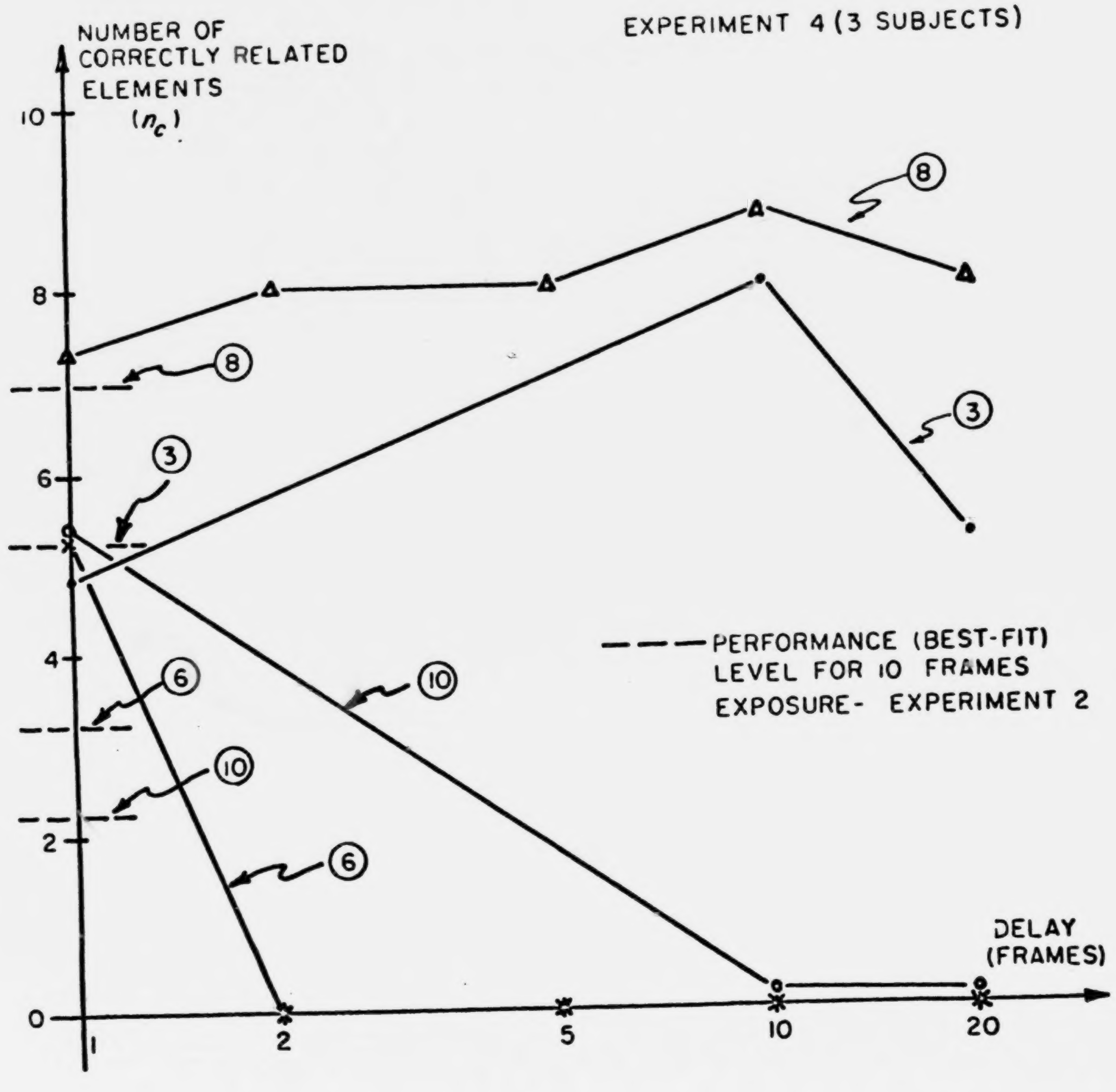


Figure 4.5. n_c *vs Delay--Sampling Experiment*

In general, as the delay approaches zero* the performance difference between patterns is much smaller with the sampling experiment than with the total-report experiment (Experiment 2). As the delay is increased, there is a marked difference between patterns. Performance with patterns (6) and (10), classified random in Experiment 1, deteriorates rapidly, with delays greater than one frame falling immediately below the chance level. The (B) pattern, also classified random, exhibits a slower deterioration of performance with delay. The structured patterns (8), (J), and (F) are characterized by high levels of performance virtually independent of delay. In general, the short-delay performance is higher than the performance measured by total report in Experiment 2. The most marked differences occur for the random patterns (6), (10), and (B), which clearly indicates the effects of short-term memory in improving performance. The small number of samples (ten) used with the (10)-patterns has the effect of exaggerating the time dependence of performance. The total number of samples identified actually falls to about one half of the one-frame delay value at twenty-frames delay. In addition, because only 22 percent of the possible element pairs are sampled for (10)-patterns, one can only interpret these results qualitatively.

4.4 Short-Term Memory Pattern Recognition in Relation to Total Report

In Experiment 2, which involves total report of the elements of a five- or ten-element pattern, the number of elements that can be correctly reported differs considerably as a function of the pattern. For instance, after an exposure of ten frames (≈ 625 msec) the average number of correctly reported elements (in the best-fit sense) was 6.8 for pattern (8) and 2.2 for pattern (10). In the sampling experiment described in section 4.3, we inferred that one frame (62 msec) after a ten-frame exposure the subject can relate about 5.2 elements from pattern (10) as opposed to 7.4 elements from pattern (8). Thus, in reports that draw information from the short-term memory, random and structured pattern sources have less influence on performance. The general compression of performance difference between patterns as measured by the sampling experiment indicates that the short-term memory provides a nearly eidetic memory component for very short delays. The extent to which this eidetic behavior is related to the detection of apparent motion in peripheral vision is not clear from Experiment 4. Wertheimer's (9) data indicate that a 60-msec delay between stimuli results

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**The best-fit grades for Experiment 2 at ten-frame exposure are plotted on the* n_c*-axis for Figures 5.4 and 5.5 for reference.*

in optimal apparent motion detection. However, the coarseness of the sampling measurement is really responsible for the sharp decay of performance. The actual decay is much more gradual, indicating that performance remains above the total report level for at least five frames.

The difference in information transmission measured with total report and the sampling technique is considerable. At one-frame delay a transmission upper-bounded by 24.4 bits from pattern (10) is measured. The upper bound on transmission for the same exposure duration (ten frames) of 10.4 bits is measured with total report.

The decay of performance for long delays to the immediate (permanent) memory level, as described by Averbach and Sperling (2), should result in a gradual decrease in n_c to the level measured in Experiment 2 for a ten-frame exposure. This decay is very slow for highly structured patterns and more rapid for random patterns [see Figures 4.4 and 4.5, patterns (B), (6), (10)]. The immediate memory level for the structured patterns is probably higher in Experiment 4 because of the large number of exposures which must be used for each pattern. Nevertheless, the decay of short-term memory to the immediate memory level is clearly demonstrated to depend upon the pattern source, with random patterns characterized by decay in two to ten frames (125 to 625 msec) and structured patterns characterized by decay in greater than twenty frames (1.25 sec). Note that pattern (B), a random (75 percent by Experiment 1) (5)-pattern, decays more slowly than pattern (6), a random (65 percent by Experiment 1) (10)-pattern; and that again the random-structured differences are more pronounced with (10)-patterns than with (5)-patterns.

4.5 Conclusions

The following conclusions describe the differences between total-report and short-term memory performance:

1. The sampling technique described in section 4.2 provides a means of measuring short-term memory effects; but the use of only ten samples for ten-element patterns results in a very coarse measurement somewhat dependent upon the samples selected. The sampling experiments, as implemented here, become impractical for more complicated patterns.

2. There is more information available in short-term memory than is reported with total-report techniques for the same exposure duration. While exact information measures do not exist for patterns, a difference of about 2:1 in bits is estimated for some patterns.

3. The short-term memory contains an eidetic component which results in more similar performance for all patterns for very short delays. The performance difference is compressed

from 1.7 elements to 1 element for (5)-patterns and from 4.6 elements to 2.6 elements for (10)-patterns.

4. The random-structured grouping serves as a basis for predicting short-term memory performance with respect to level for short delays and nature of decay with increasing delay. Random patterns decay faster than structured patterns; this effect is more pronounced for (10)-patterns than for (5)-patterns. While decay to the immediate memory level has not been demonstrated, we estimate that this decay requires less than five frames for random (10)-patterns and more than twenty frames for random and structured (5)-patterns, with structured (5)-patterns showing no appreciable decay up to twenty frames (1.25 sec).

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5. SOME SYSTEM ASPECTS

In sections 3 and 4 the major emphasis was on performance as a function of the properties of the spacial distribution of pattern elements. In this section several aspects of vision that are not particular to detailed spacial distributions are discussed. The effects of dispersion or size, duration of the glance, the element context, and eye motion are considered. Some experiments intended to point out these effects are included in this section. And, results reported in Appendixes A and C are related to the pattern-recognition experiments.

5.1 Total Report and Pattern Recognition from a Linear Array

The major difference between Experiments 3 and 3A and other tachistoscopic investigations using arrays of English letters is that the exact position of the letters is unknown to the subject until the pattern is exposed (1, 2). In addition, the array is large (10 deg in the horizontal direction by about 7 deg in the vertical direction), and the number of letters in each array is unknown (to within one of two possibilities). Furthermore, the results of Experiment 3 indicate that, under the circumstances described above, about one letter less can be reported on the average from ten-letter patterns than from five-letter patterns for exposure durations between two and twenty frames. To help explain this phenomenon and assess the effects of unknown positions within the array, the following experiments were conducted.

Experiment 5A

Six subjects were exposed to a sequence of twelve arrays of ten letters each, chosen from zero-gram English. The letter array, consisting of two rows of five letters each occupying adjacent positions in the pattern matrix (see Fig. 5.1, sample array A), was shown to the subjects before the experiment, and a few sample exposures preceded the test exposures. Experimental conditions were identical to those in Experiment 3, except that two different sets of letters were used at each exposure duration. Exposure durations of 1, 2, 5, 10, 20, and 50 frames were used in a random order. The subjects responded by marking down as many letters as possible from each exposure, beginning their report after the exposure was over. The movie (and experiment) running time was about three minutes.

Experiment 5B

Experiment 5B was identical to 5A except for the letter array used. A more widely spaced two-line array (see Fig. 5.1, sample array B) centered at approximately the middle of the pattern matrix was chosen. The same exposure durations were used with the same six subjects. This experiment followed Experiment 5A and ran for approximately three minutes.

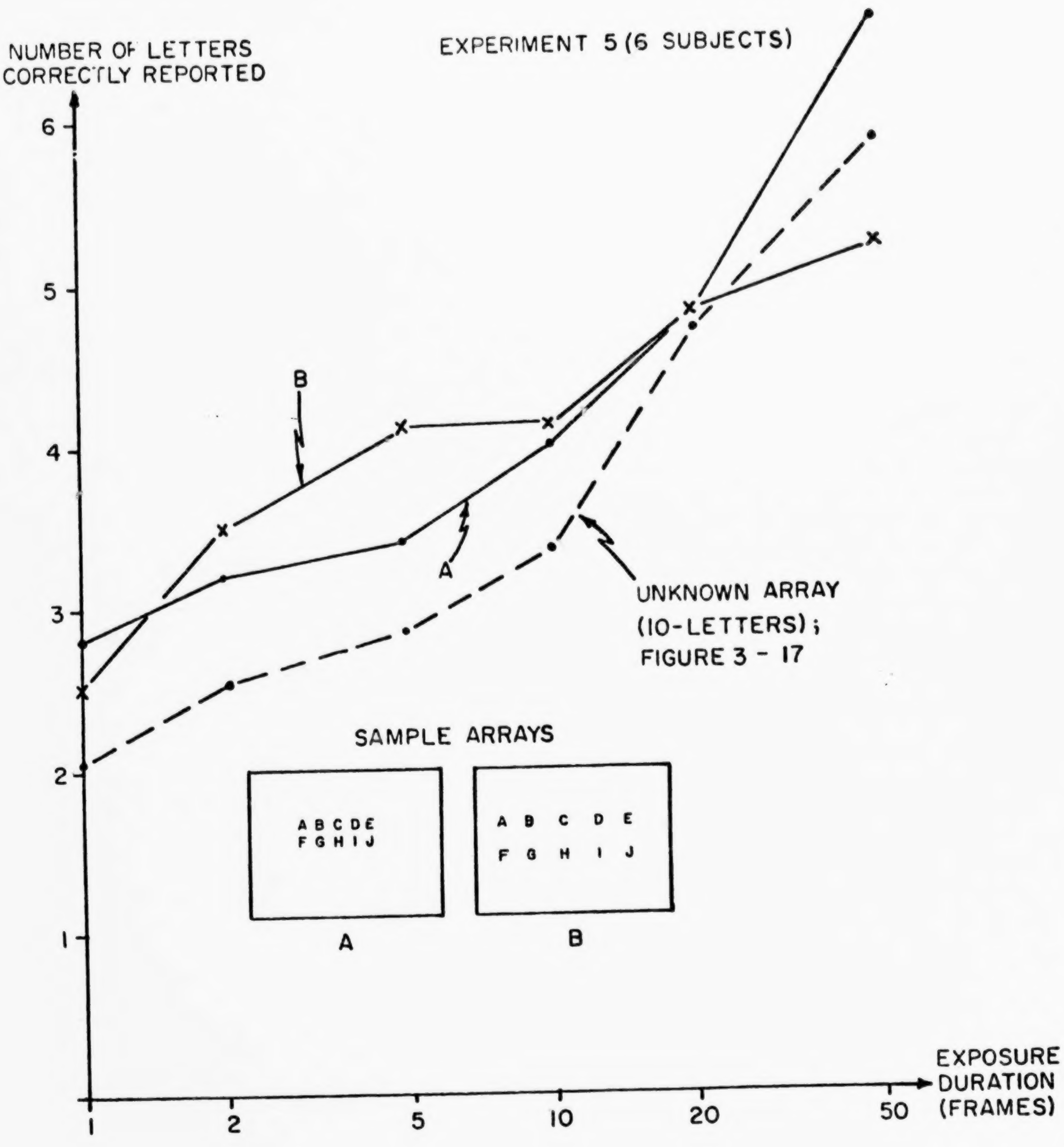

Figure 5.1. Letter Report from Known Spacial Arrays

The results of these experiments are plotted in Figure 5.1. The letter recall for the shortest exposures differs by only 0.5 to 0.7 letters (on the average) from the results of Experiment 3 with unknown arrays. After about twenty frames (approximately 1 sec) the fact that the array is unknown makes little difference in performance. Presumably, the eyes have ample time to search the matrix for durations of this length. Note that the unknown arrays [in this case, patterns (1), (2), (6), (8)], in general, are more dispersed than either of the known arrays (A and B). Thus, it cannot be said with certainty whether dispersion or lack of a priori letter-position knowledge is responsible for the difference between the A curve and unknown array curve in Figure 5.1.

The difference between performance with array A and array B is also worthy of comment? the larger array is conducive to better performance (by an average of 0.6 letters) for short durations. This difference (almost identical to that between five-letter and ten-letter curves in Fig. 3.17) strongly suggests that dispersion helps performance for a range of exposure durations when one is concerned with the report of unrelated items. In both the A- and B-array experiments the percentage of incorrectly reported letters was 2.5 to 3 percent. Thus, confusion caused by proximity is not the major cause for the difference in performance. Furthermore, these conclusions can be extrapolated to the unknown array situation (Experiment 3) and result in complete agreement with measured performance. Consider the letter-report curves for patterns (H) and (J) in Figure 3.18 and patterns (1) and (8) in Figure 3.19. Pattern (1), a symmetric dispersed array quite similar to known array B, begins significantly poorer than (8), but, for two- and ten-frame exposures, results in improved performance. Pattern (H), a larger inverted version of (J), results in improved performance for one- and two-frame exposures.*

The long-duration asymptotes, though their difference in the three curves in Figure 5.1 is only about 1.2 letters, are also consistent with data for individual unknown arrays. Curves A and B indicate that dispersion results in lower performance for long-duration exposures. The unknown curve lies between A and B, and it is clear that for the unknown patterns used any six or so elements are less separated than those in B.

Simple pattern-recognition experiments also were performed with a 1 x 6 linear array of black and white squares or numerals (see Figs. A.1 and C.6). Details are discussed in Appendixes A and C. The experiments are cited here (*1*) to demonstrate spacial span of apprehension in the horizontal and vertical directions,

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**Note that this is exactly opposite to performance in Experiment 2 for the same patterns.*

and (2) to demonstrate ways in which performance in pattern-recognition tasks involving short-duration exposures may be modified virtually independent of the stimulus details.

Figure 5.2 demonstrates position-error distributions averaged over all the exposure durations for independent measurements with a vertically and horizontally oriented 1 x 6 array. Subjects were asked to indicate the positions of the white squares in each short-duration exposure which consisted of one, two, three, or four white squares. The vertical error characteristic is almost exactly the same as the horizontal error characteristic rotated 90 deg clockwise, the same rotation applied to the display matrix to project the array with vertical orientation. Thus, subjects perform better going from top to bottom and from left to right. The data in Figure 5.2 show that subjects are equally adept at horizontal or vertical position location. The effect of edge cues is also apparent from this figure. The lowest errors occur at the top and bottom and left and right edges of the display.

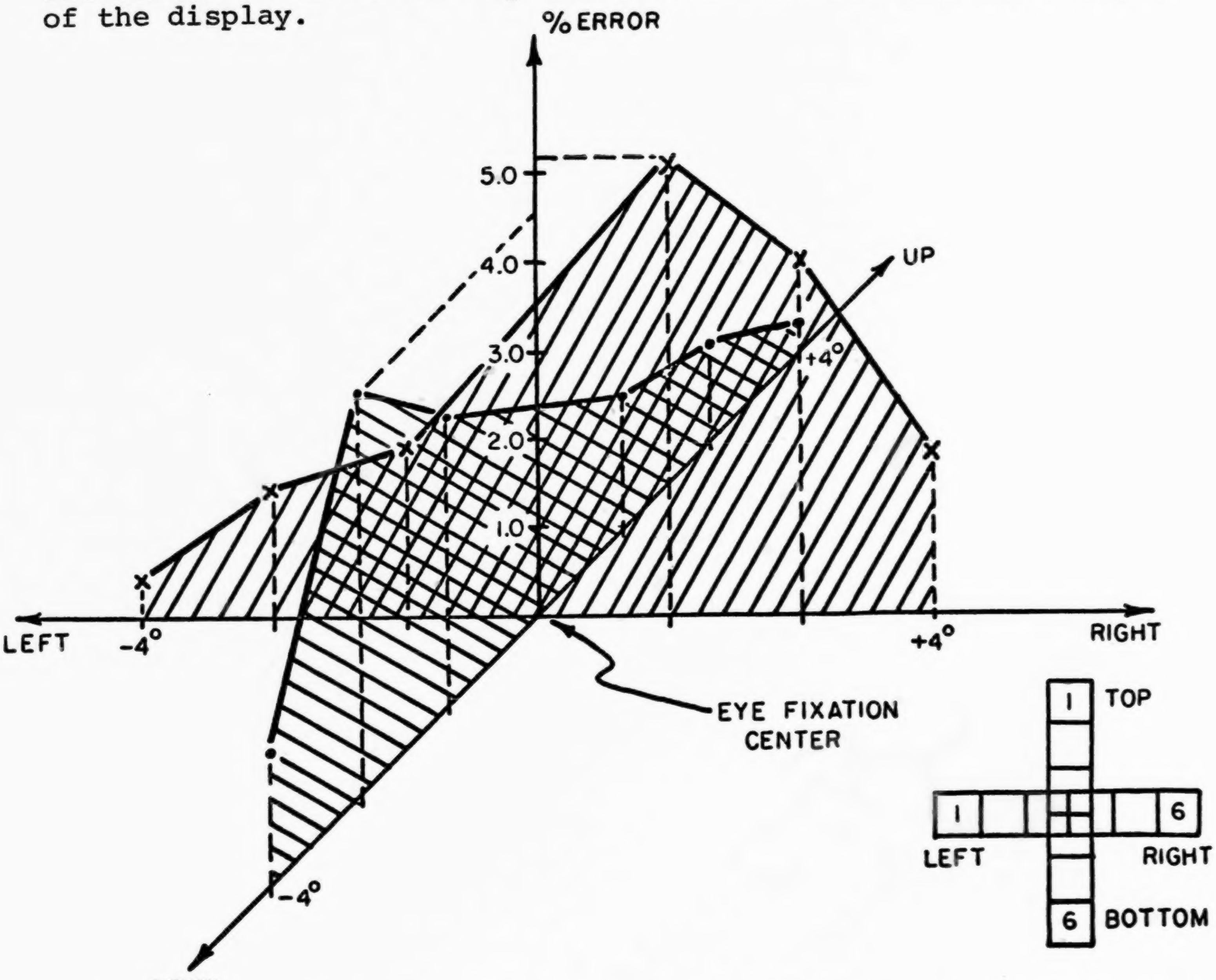


Figure 5.2. Horizontal and Vertical Position Error Distribution

The curve in Figure 5.2 demonstrates what might be termed the average subject's spacial span of apprehension bias (for an array of dimension 6). This bias, which is indicated in the results of position-report accuracy discussed in section 5.4, is felt to be a general aspect of behavior with matrix patterns.

The error-versus-exposure-duration curves for the same stimulus material (Figs. A.2, C.3, and C.4) exhibit pronounced peaks at intermediate durations for numeral-report and position-report experiments. These curves indicate that increased exposure to the stimulus material does not result in improved performance for all cases. The naive notion that information processing occurs at a constant rate through the one-glance region cannot be applied to all stimulus exposures. Furthermore, the exposure durations at which increased confusion occurs (approximately 50 to 100 msec) are close to exposure durations for which the Broca-Sulzer phenomenon (3) has been shown to cause artificial brightness enhancement (50 msec) and to the latency interval for voluntary eye motion (4). Note that seven of the twenty patterns used in Experiment 2 with best-fit grading exhibit poorer performance at exposure durations of two frames (approximately 120 msec) than at one frame. Thus, aspects of the visual system serve to complicate the considerations upon which any processing model of a general nature is based.

5.2 Eye Motion Effects in Dispersed Patterns

It was pointed out in section 2.4 that eye motion becomes a significant aspect of information retrieval from large patterns (up to 10 deg) for short-duration exposures. In general, the eye executes a position-versus-time curve which involves the superposition of three motion components?

1. An eye tremor of small amplitude (a few seconds of arc) at frequencies of 30 to 70 cps;
2. An erratic random motion of larger amplitude than (1);
3. The voluntary and involuntary gross eye motions required to compensate for head motion and object tracking (5, 6).

The gross motion effects required for object tracking or recognition of dispersed patterns are of particular interest here. Though the exact mechanism whereby eye motion is required in vision is not well understood, there is positive evidence that visual acuity is seriously affected when it is suppressed. Ditchburn and Ginsborg (7) and Ditchburn and Fender (8) have shown that when the position of an object is stabilized on the retinal surface, acuity is often lost entirely.

In this section measurement of gross eye motion for dispersed patterns is considered to provide a basis for interpretation (at least with respect to eye motion) of the various pattern-recognition results reported earlier. A psychophysical estimate of dispersion effects is discussed in the next section.

Basically, there are two ways in which the position of the eye with respect to the head may be measured. The first involves electrical recording of the polarization potential of the eyeball (9). The second involves measurement of reflected light either directly from the cornea or from a small mirror ground on a contact lens placed over the cornea (10). The author used a device suggested by Richter and Pflatz (11) and developed by Dr. Lawrence Stark and Messrs. Laurence Young and Alan Sandburg (12) of the MIT Electronic Systems Laboratory for the horizontal eye position. This device measures the difference in the amount of light reflected from the dark iris area and "white" (sclera) of the eye as a function of eye position. It permits the measurement of eye position (via a dc output signal) to an accuracy of about 5 percent after appropriate calibration. Because it only provides a measure of horizontal eye position (in its present form), the horizontal 1 x 6 matrices used in the experiments described in Appendixes A and C were the input stimuli.

In a typical measurement situation the subject is seated 6 ft from a curved screen. His head is held rigid in an ordinary baseball catcher's mask, and a pair of clear plastic goggles, which contain the light sources and reflection measurement sensors, are placed over his eyes. Figure 5.3 depicts the measurement configuration. A dual-track chart recorder monitors the projection flash and the dc signal proportional to horizontal eye position.

The results of a limited measurement program using this technique provide interesting, objective eye motion data for further interpretation of the psychophysical results. Four measurements of eye motions were made for two subjects under various stimulus conditions?

1. Exposure to numeral plus position display (Fig. C.6 at 30-msec duration.
2. Exposure to numeral plus position display (Fig. C.6 at 100-msec duration.
3. Exposure to position-only display (Fig. C.1, horizontally oriented) at 60-msec duration.
4. Exposure to position-only display (Fig. C.1, horizontally oriented) at 100-msec duration.

In all cases the horizontal extent of the projected pattern was about 9 degs. The measured data are summarized in Figures 5.4, 5.5, and 5.6 and in Table 5.1. Figures 5.4 and 5.5 represent typical eye motion traces from the Sanborn recorder for the four stimulus conditions. These traces are typical of the many recordings made for each condition. All the recordings show a large sinusoidal baseline noise level due to electrical disturbances created by the projector blower and all are for the same subject. In Figure 5.5a the 60-msec light pulse has been emphasized for clarity. All other light pulses (upper traces) begin with the sharp upward departure from the baseline and end with the beginning of the negative backswing. The results of other typical recordings (not depicted) are summarized in Table 5.1. The results of these measurements are summarized below.

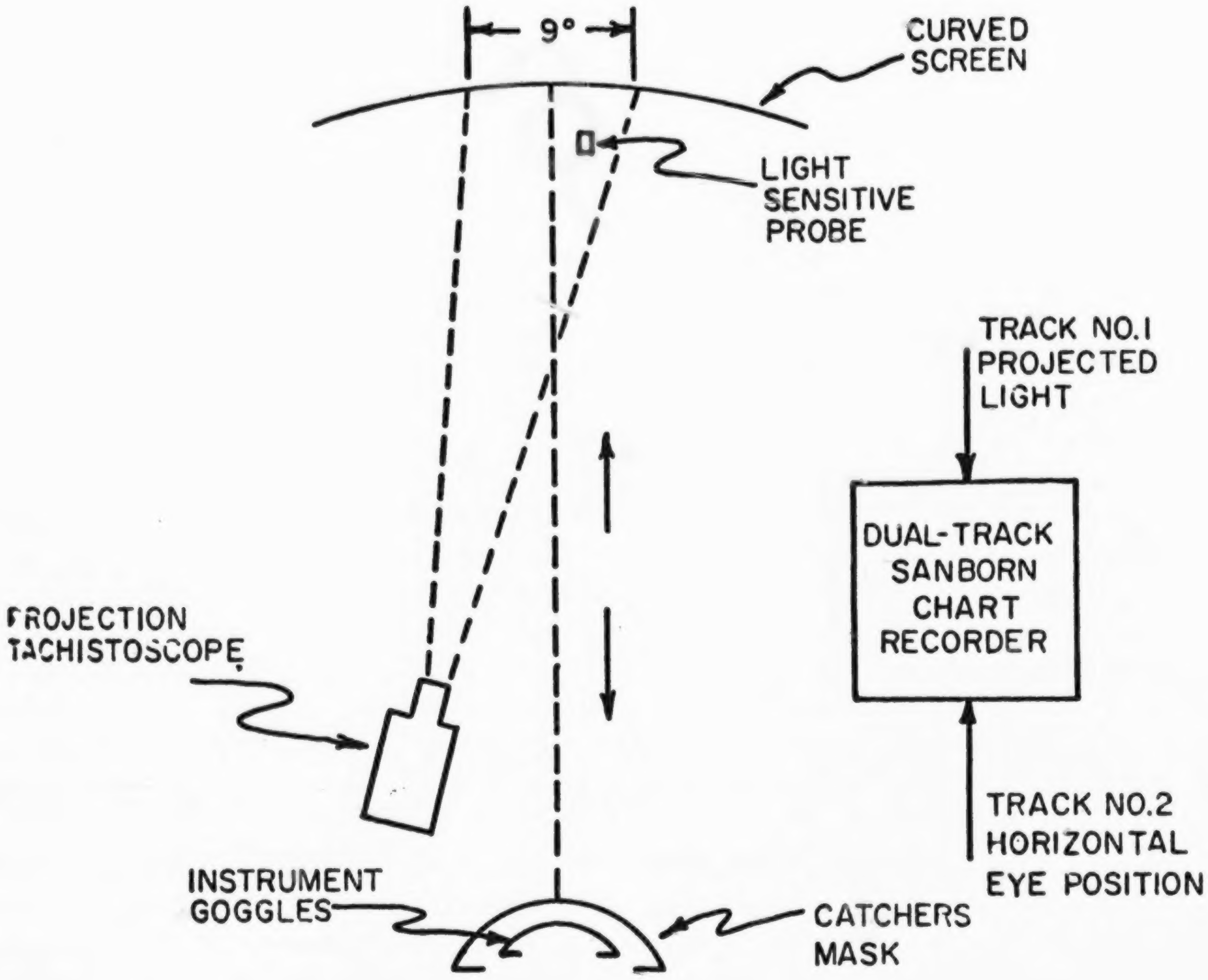
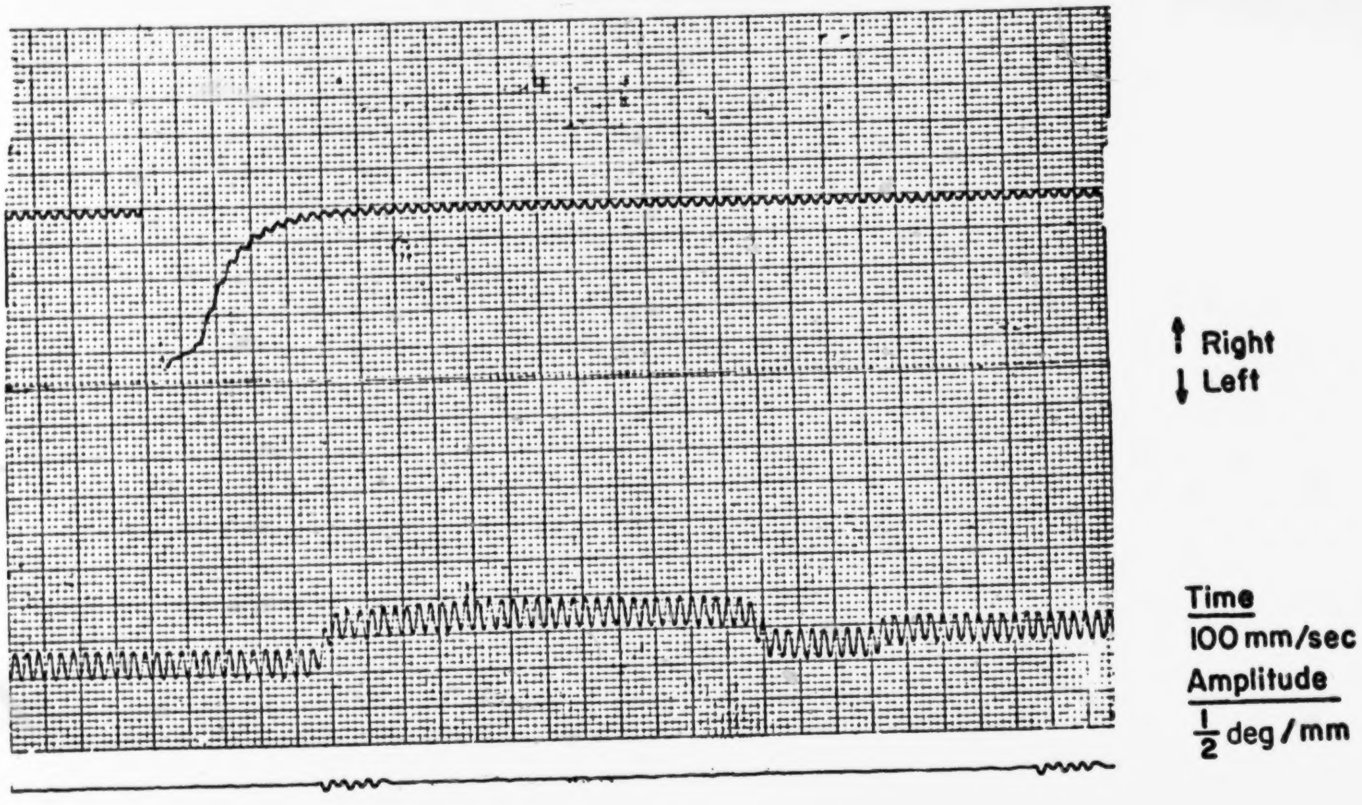

9°
CURVED SCREEN
LIGHT SENSITIVE PROBE
TRACK NO.1 PROJECTED LIGHT
DUAL-TRACK SANBORN CHART RECORDER
PROJECTION TACHISTOSCOPE
TRACK NO.2 HORIZONTAL EYE POSITION
INSTRUMENT GOGGLES
CATCHERS MASK

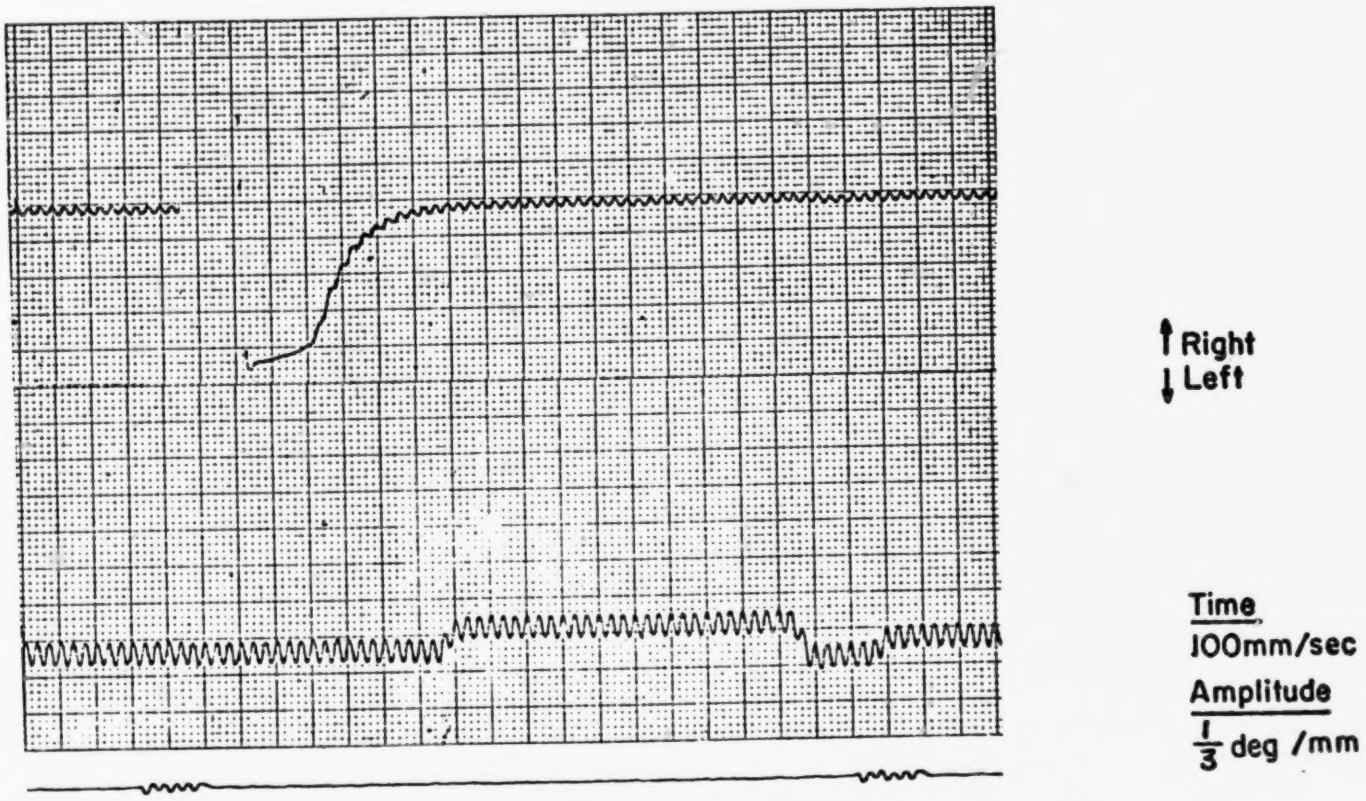
Figure 5.3. Horizontal Eye Motion Measurement Configuration

1. No significant eye motion (none greater than 1/2 deg) occurs during exposures up to 100-msec duration. In general, latency increases as the flash duration is decreased. The average latency for 100-msec flashes is about 240 msec as opposed to 275 msec for 30-msec flashes. The latency is shorter when position-only displays are used (averaging about 175 msec).

2. Postexposure eye motion differs in accordance with the stimulus material. Numeral plus position displays are followed by greater motion almost invariably involving a center-to-right-to-center-to-left-to-center sequence, causing excursions of about 3 deg right of center to 2 deg left of center, with fixation intervals varying from 150 to 700 msec (see Fig. 5.6). Position-only displays almost invariably are characterized by less postexposure motion between the center and right (2 deg). This motion takes place much more slowly than comparable excursions with numerals.

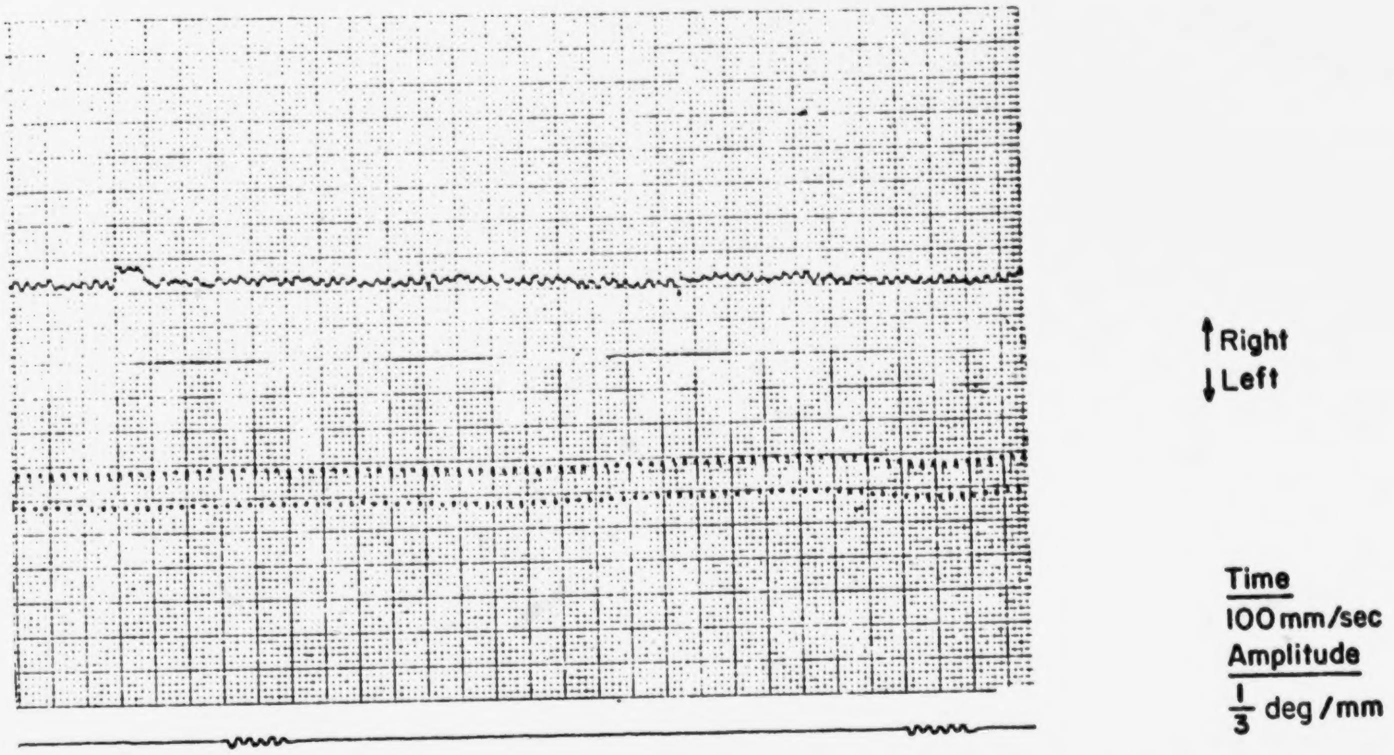


(a)
30 msec Exposure

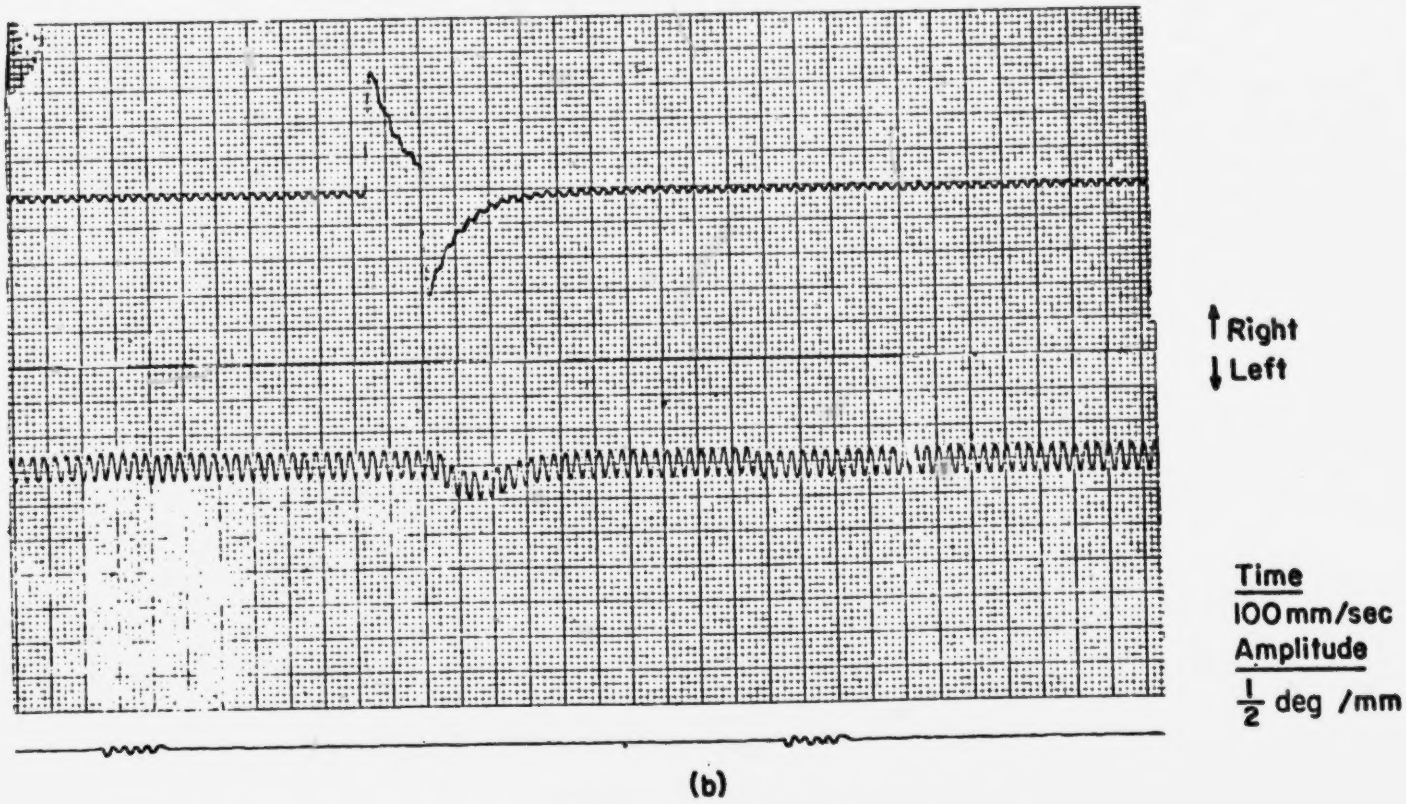


(b)
100 msec Exposure

Figure 5.4. Horizontal Eye Motion Recordings--Numeral plus Position Display



(a)
60 msec Exposure



(b)
100 msec Exposure

Figure 5.5. Horizontal Eye Motion Recordings--Position-Only Display

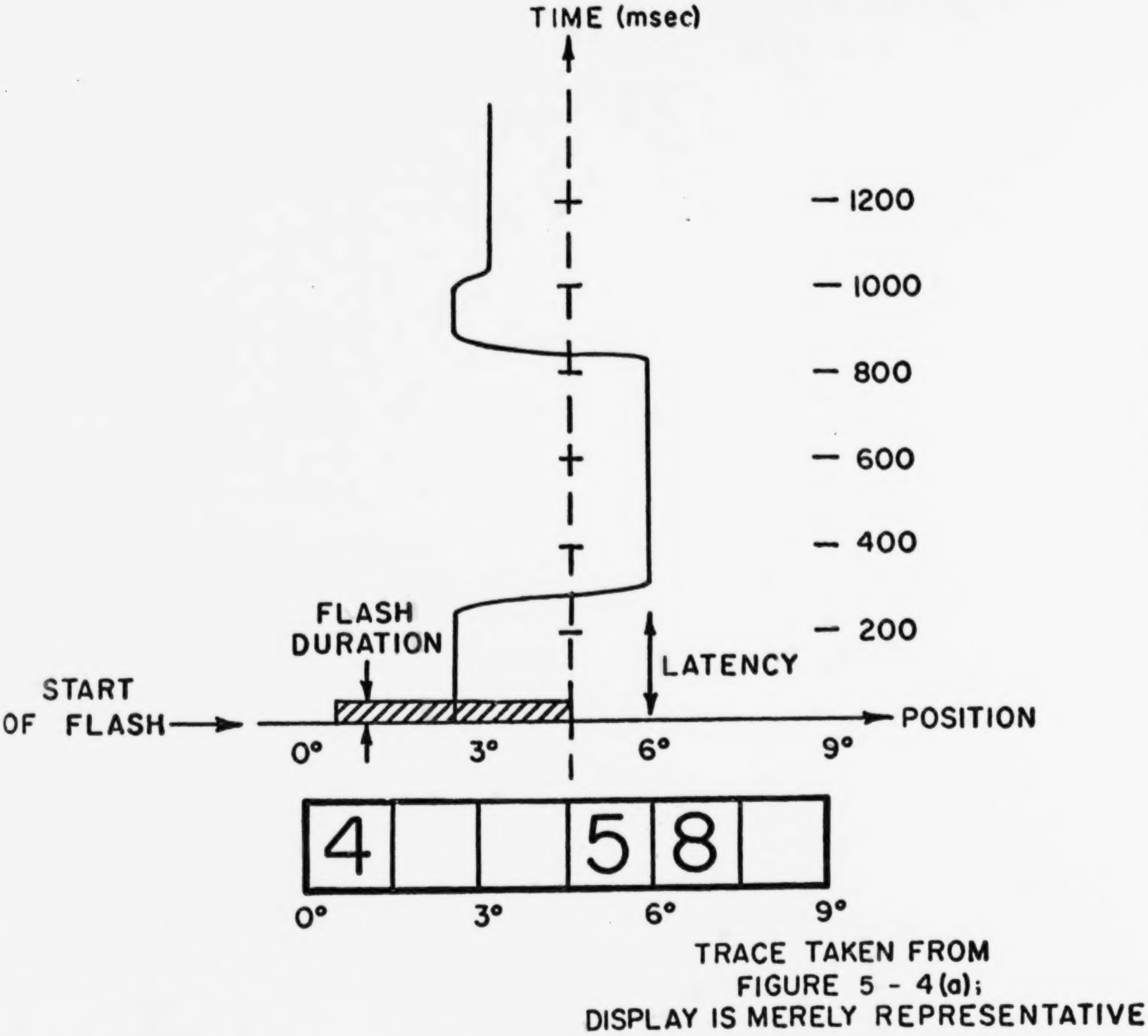

TIME (msec)
1200
1000
800
600
400
200
FLASH DURATION
LATENCY
START OF FLASH
POSITION
0°
3°
6°
9°
4
5
8
0°
3°
6°
9°
TRACE TAKEN FROM FIGURE 5 - 4(a);
DISPLAY IS MERELY REPRESENTATIVE

Figure 5.6. Eye Position vs Time--Numeral plus Position Display

3. At 60-msec exposure duration with position-only displays, virtually no motion is recorded except a very slow drift less than 1/2 deg in amplitude. This duration and stimulus result in the highest error for the experiments described in Appendix A.

These results are in general agreement with those in the literature (4).

In discussing explanations for psychophysical performance, it is a reasonable assumption that eye motion is not involved as such for exposure durations less than about four frames.

Table 5.1

Eye Motion Data Summary

Exposure Description	*Trace*	*Latency*	*Maximum Right and Left Excursions*	
(1) 30-msec duration, numerals plus position display	1	230 msec	R--3°	L--1°
	2	300 msec	R--1-1/2°	L--1/2°
	3	270 msec	R--1-1/2°	L--1/2°
	4	250 msec	R--2°	L--1/2°
	5	300 msec	R--1-1/2°	L--1-1/2°
	6	270 msec	R--1°	L--1°
	7	300 msec	R--1°	L--1°
(2) 100-msec duration, numerals plus position display	1	230 msec	R--3°	L--1/2°
	2	250 msec	R--1°	L--2°
	3	250 msec	R--1/2°	L--1/2°
	4	250 msec	R--2-1/2°	L--2-1/2°
	5	320 msec	R--3°	L--1-1/2°
(3) 60-msec duration, position-only display	12	avg ≈ 200 msec	Very little motion; all less than ±1/2 deg from center	
(4) 100-msec duration, position-only display	1	200 msec	R--1-1/2°	
	2	220 msec	Very little	
	3	150 msec	L--1/2°	
	4	125 msec	L--1/2°	

5.3 Psychophysical Estimate of Dispersion Effects

A psychophysical experiment was conducted to illustrate the effects of display dispersion on performance. The task selected for testing involved counting the number of times in a long sequence that three English letters projected simultaneously were identical. To eliminate confusion and minimize the effects of reading different letters, alternate exposures in the sequence were drawn from the A-B and C-D ensembles. Twenty exposures were used in each run. At each combination of single-exposure duration and distance between letters, a high and low count run were used.

Experiment 6

Ten subjects were exposed to 32 runs of three-letter exposures similar to the run shown in Figure 5.9. Exposure times were 1, 2, 5, and 10 frames; distances were 1.3, 2.1, 5, and 8.8 deg. In all cases the center letter was not moved/ distance was varied by equal separation of the right and left letters. A typical run began with a 2-sec black interval (call to attention) exposed. This interval was followed by a 2-sec white interval, followed by the 20-exposure run. After the run a 10-sec report interval was projected. The subjects were instructed to count the number of times in each run all three letters in an exposure were the same--that is, AAA, BBB, CCC, or DDD. A high count run (11 to 15) and a low count run (5 to 9) was used at each experimental point (distance-duration). Subjects reported by writing their count for each run on an answer sheet. Two subjects, seated to the right and left of the projector at a distance of 9 ft, were tested in each session. The running time of the film (including a few practice runs) was about 14 min.

The results of Experiment 6, which are plotted in Figures 5.7 and 5.8, demonstrate that in general, performance improves, with increasing exposure duration and decreasing distance--a perfectly reasonable result. The one exception is demonstrated graphically by examining the 1.3-deg and 2.1-deg separations at an exposure duration of five frames (approximately 310 msec). These points indicate that increased separation at constant exposure duration is required to improve performance. In the absence of other corroborating data, one might dismiss this relation as a product of experimental inaccuracy. However, Figure 5.1 shows that at five-frames duration subjects are able to report significantly more letters from a dispersed array than from a closely spaced array. The distances between letters in these arrays (Experiment 5) are of the same order of magnitude as the distances involved in Experiment 6.

A significant experimental artifact is demonstrated by this experiment. The data in Figure 5.8 for durations of one and two frames are more a measure of counting speed than letter comparisons and the tracking required to make them. For one-frame duration per exposure, the entire twenty-exposure run lasts about 1.25 sec. If there are 15 correct counts in this interval, the subject is counting at an average rate of about 12 counts/sec. A preliminary pilot film and very limited testing indicated that subjects could count conveniently only at rates of about 2/sec. Thus, it appears that the counting problem is the major difficulty encountered at one- and two-frame exposures. However, the data are consistent (as evidenced by the curves in Fig. 5.8); and, more important, the subjects invariably report more counts for the high-count run than for the low-count run at each duration-distance measure. (See Table B.7, Appendix B.)

The author finds this result surprising because the subject has no way of knowing the correct count for any run. One explanation lies in the subjective data volunteered by some subjects. First, it is virtually impossible to count anything at all for the short-duration runs in the normal manner. Only the first letters are seen if the eye continues uninterrupted fixation. Every other letter is seen as a blur because of temporal stimulus masking (13). However, many subjects reported blinking their eyes and "now and then picking up a count."

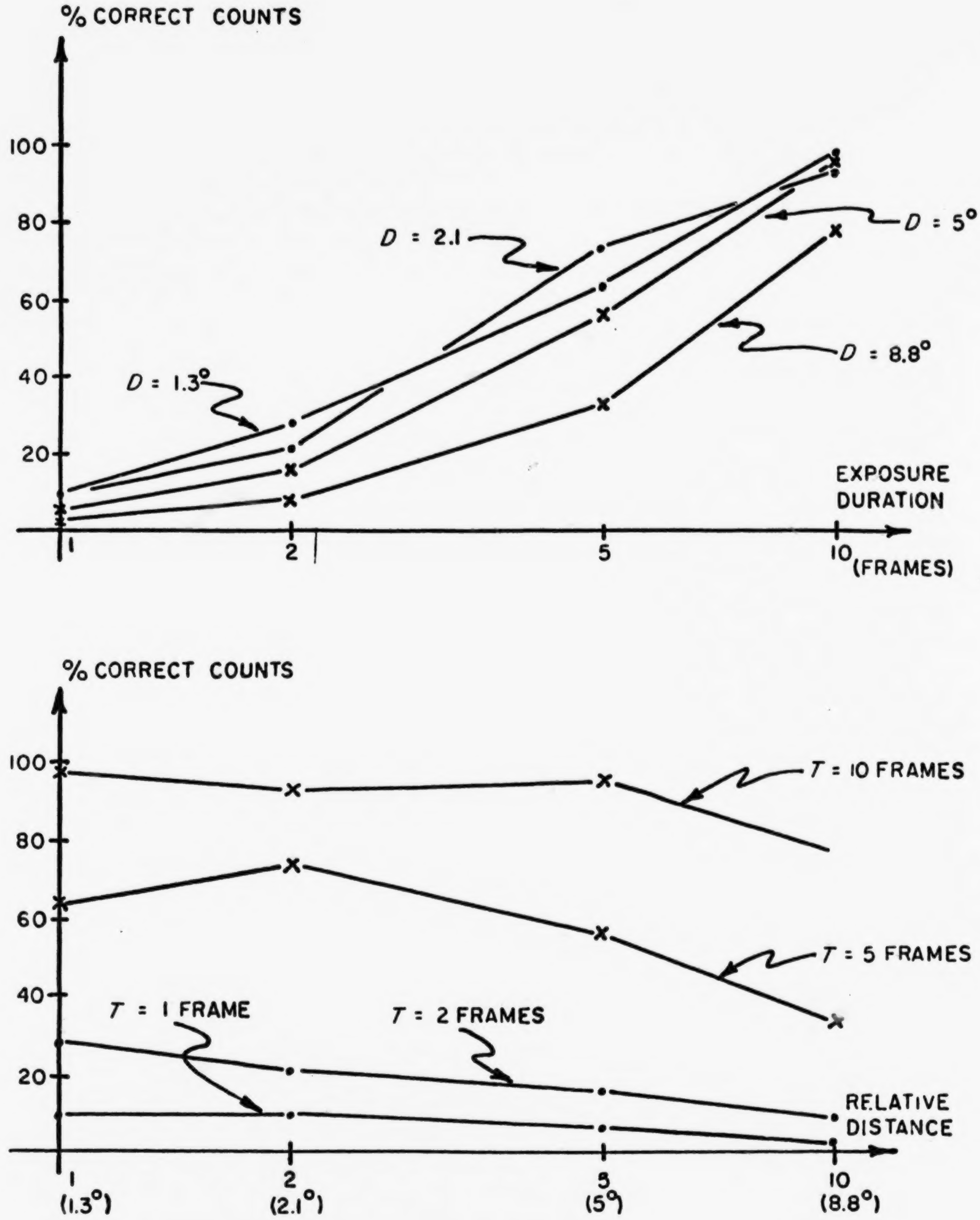


Figure 5.8. Percent Correct Counts vs Relative Distance--Experiment 6

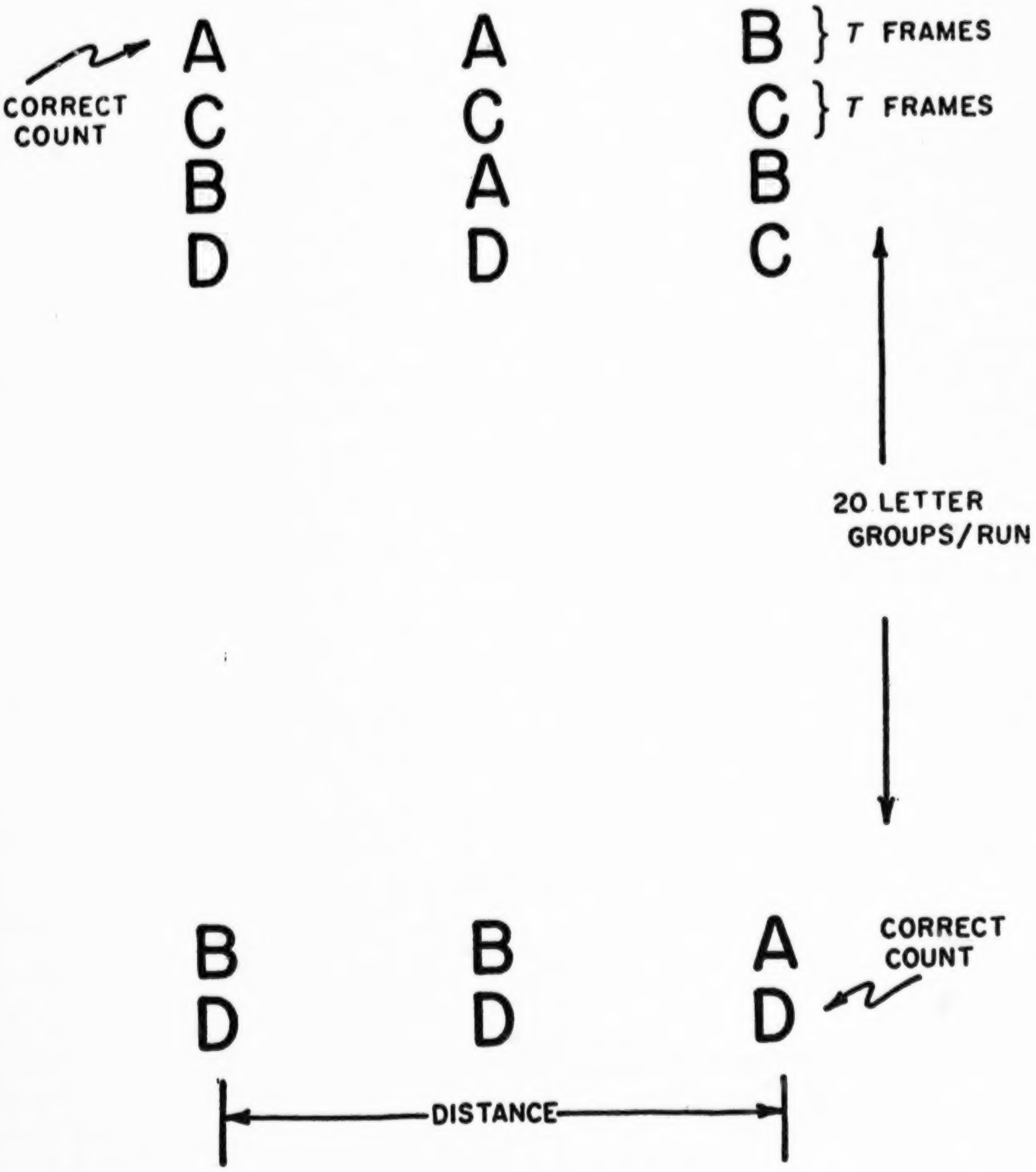

CORRECT COUNT
A
C
B
D
A
C
A
D
B
C
B
C
T FRAMES
T FRAMES
20 LETTER GROUPS/RUN
B
D
B
D
A
D
CORRECT COUNT
DISTANCE

Figure 5.9. Typical Letter Run--Experiment 6

Blinking avoids masking by previous letters and should result in a count proportional to the number present when averaged over several subjects.

Data from the literature (14) as well as the measurements described in section 5.2 indicate that saccadic motions of the order of 10 deg can be made at rates up to 300 deg/sec after appropriate latency (in this case, presumably at the outset of a run). Thus, a considerable amount of motion can occur during each one-frame exposure. The deterioration in performance is thus seen to be due to the fixation time required at each point for data analysis.

The major psychophysical result of this experiment is that dispersion effects (10-deg dispersion) have been shown to be significant up to about ten-frames duration (where counting difficulty disappears). The curve of percent correct counts versus distance at T = 10 frames in Figure 5.8 serves to define a "spacial span of apprehension" of 5 deg for letter comparison.

5.4 The Problem of Recognition in Context

Clearly, what we are able to recognize from any display depends upon the context (rest of the display) as well as the particular recognition task under consideration. Sprinkled through the literature are numerous examples of the influence of context on task performance. Contextual relations have been shown to operate in rather complicated ways in short-term visual memory (13). The error-versus-display-position curves for linear displays of letters reported by Averbach and Coriell (15) indicate a simpler problem of recognition in context as do the error-versus-position curves in Appendixes A and C. The curves in Figure 5.1 strongly indicate that letter separation (size context) may be optimized for maximum report at given exposure durations. In this section a general hypothesis is suggested to explain various contextual problems.

To pursue this problem further, we shall analyze the results of Experiments 2 and 3 from a different point of view (see Fig. 5.10). This figure compares success with best-fit grading in Experiment 2 with letter recognition in Experiment 3 for individual element positions. It should be recalled that patterns consist of related elements (strongly related elements), while letter recognition involves the recall of unrelated items. The data in Figure 5.10 have been averaged over all subjects and all durations. Percentages refer to the results of Experiments 2 and 3, and because the average performance was different in these two experiments, the figures must be carefully interpreted.

Beginning with pattern (H), we see that the center element is reported correctly more often in letter recall than pattern recognition (by approximately 2 to 1), while the reverse is true of the center element of pattern (J). At this point we shall state a general hypothesis:

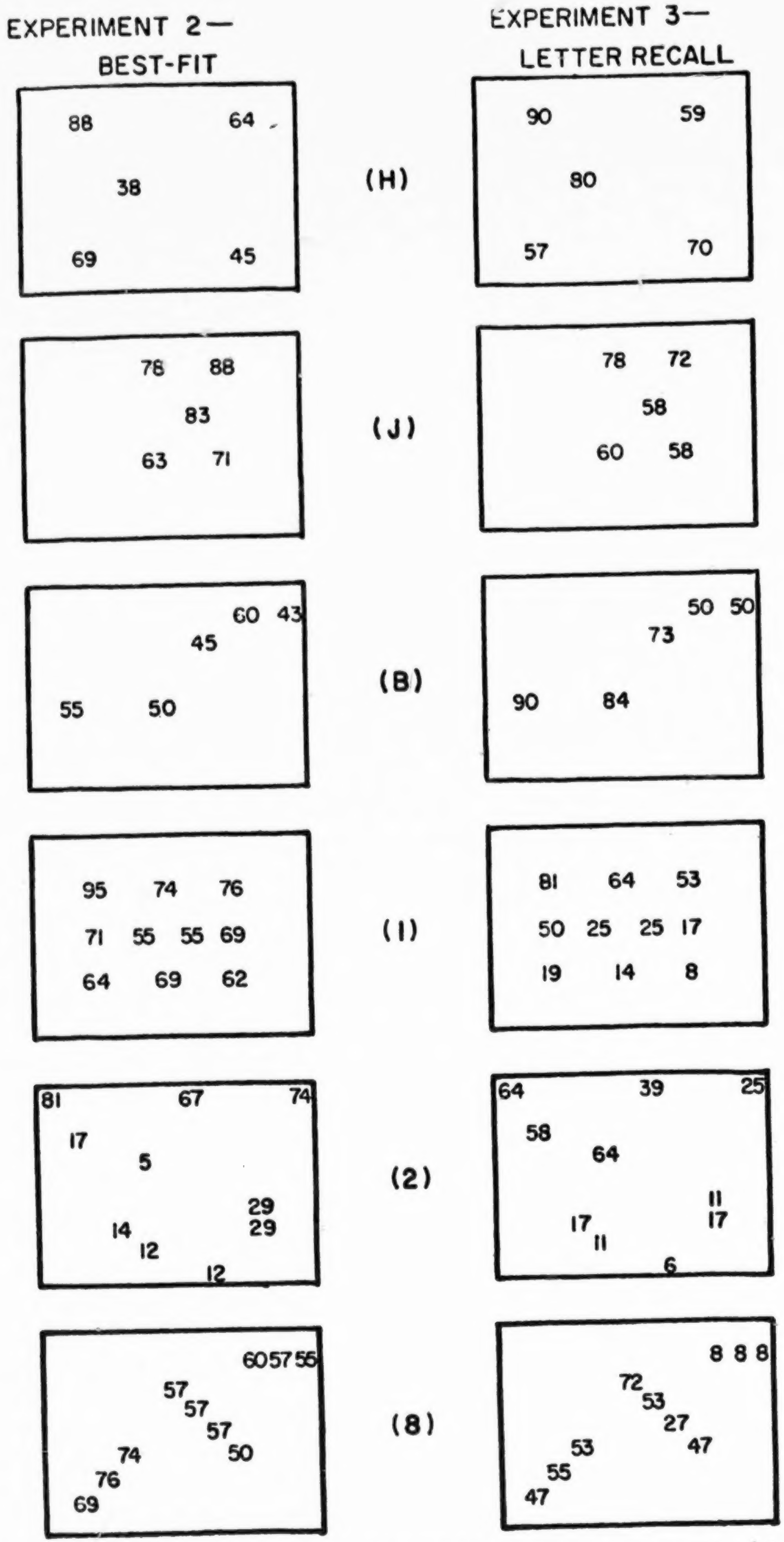

EXPERIMENT 2— BEST-FIT
EXPERIMENT 3— LETTER RECALL
88 64 38 69 45
(H)
90 59 80 57 70
78 88 83 63 71
(J)
78 72 58 60 58
60 43 45 55 50
(B)
50 50 73 90 84
95 74 76 71 55 55 69 64 69 62
(1)
81 64 53 50 25 25 17 19 14 8
81 67 74 17 5 29 29 14 12 12
(2)
64 39 25 58 64 11 17 17 11 6
60 57 55 57 57 57 50 74 76 69
(8)
8 8 8 72 53 27 47 53 55 47

Figure 5.10. Percent Correct Report vs Position--Experiments 2 and 3

Proximity and containment enhance the report success of related items while reducing report success of unrelated items.

Pattern (1) further illustrates this point, as does pattern (2) with respect to the two element pairs, and pattern (8) with respect to the lineal segments of the array.

Proximity to the edges or borders enhances recognition of pattern elements but offers little help to letter recall [see patterns (2) and (8)]. Furthermore, grouping of unrelated items does not enhance letter recall but definitely aids pattern element recall.

It is clear from virtually all of the letter-recall patterns that subjects read letters (or scan in search of letters) mainly from left to right and to a lesser extent from top to bottom. The same statement is not necessarily true for pattern items [see (B), (H), and so on].

In addition to the convenient discussion of the context problem offered by the data in Figure 5.10, the same general concepts are completely applicable to letter-recall data from Experiment 5 and Experiments C.1 through C.4, and also applicable to the data presented by Averbach and Coriell (15).

The problem of recognition in context is not completely solved with the above considerations. However, they do help demonstrate a significant aspect of visual pattern recognition.

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6. CONCLUSIONS

In this section various conclusions reached in the body of the text are summarized and future work directly related to this research is discussed.

6.1 Summary of Basic Pattern-Recognition Results

This thesis is concerned with the recognition of visual patterns of considerable size (10 deg) in one-glance exposures lasting from about 60 msec to 3 sec. The experimental technique selected for this investigation involved the use of motion picture stimulus displays and psychophysical reports by the subject either written or verbal. Two types of spacial distribution were used to accentuate operational principles in recognition: one involved English letter displays (unrelated elements); the other involved patterns (related elements). And two types of report were used: total report to measure span of immediate memory, and a sampled report to illustrate the role of short-term memory. The stimulus ensemble was designed to be large enough to provide for separation of pattern recognition and pattern registration. To implement this separation, a best-fit grading technique was employed in pattern-recognition experiments to provide a basis for comparison of best-fit and absolute registration grades. The gross features of eye motion (in the horizontal direction) were measured in connection with lineal visual patterns of 9 deg horizontal extent. Effects of pattern source dispersion were also demonstrated psychophysically. In addition, the problem of recognition in context for related and unrelated elements was explored. A summary of conclusions follows:

1. The motion picture technique for the presentation of short-duration visual stimuli with a wide variety of preexposure and postexposure fields, dynamic light intensity range of 10 db, and provision for image size variation has been demonstrated successfully. The ease with which completely preprogrammed experiments may be conducted further enhances the attractiveness of this technique.
2. Completely subjective classification of five- and ten-element patterns from a 9 x 12 matrix into random and structured groups provides a basis for performance prediction for both total-report experiments and short-term memory experiments. In general, there is less difference in total-report performance between random and structured (5)-patterns than (10)-patterns for short-duration exposures. The single dominant feature in performance between random and structured patterns of both sets is the sharp upward slope in performance that generally occurs after two frames of exposure. This is the shortest duration for which voluntary eye motion can occur. Thus, it is concluded that eye motion is essential to the recognition (for reproduction) of patterns from a 9 x 12 matrix ensemble subtending angles up to 10 deg to the observer.

3. An upper limit of about sixteen bits of information can be transmitted in a single glance (of three seconds duration) from the (10)-pattern source; about nine bits can be transmitted per exposure from a (5)-pattern source. The number of elements that saturate the span of immediate memory varies by more than 3 to 1 between random and structured (10)-patterns, and 1.5 to 1 with (5)-patterns.

4. The short-term memory connected with visual pattern recognition has been demonstrated to store more information than is available through total report. This storage capacity, which is dependent upon the nature of the patterns, is at least 2.5 times the information available in total report. The decay of short-term memory is a function of the pattern type. Random patterns decay quickly (less than five frames), while structured patterns are characterized by performance higher than the total-report level for at least 1 sec. Furthermore, the compression of performance difference between random and structured patterns at very short delays indicates that the short-term memory acts as an eidetic storage for short lengths of time.

5. Total report from unknown arrays of English letters subtending angles of 10 deg to the subject is shown to be virtually independent of the number of letters in the array (for $n = 5$ and $n = 10$) for exposures of one and two frames (62 and 125 msec). For exposures between two and twenty frames (125 msec to 1.25 sec) lower letter density five letters) results in improved performance (by about one letter). This fact is further substantiated by the results of experiments with known arrays of ten letters when closer spacing deteriorates performance by as much as one letter (in four) for exposure durations between two and twenty frames. The effect of unknown letter positions within a 9 x 12 matrix is to reduce letter recall by an average of about 0.8 letters for exposure durations up to twenty frames (1.25 sec). The long exposure, unknown array letter-recall results indicate that the number of letters reported is independent of the letter array. In contrast, when the same letter positions are used to form a matrix pattern, the greatest difference in performance occurs for long-duration exposures. The maximum number of letters that can be reported in one glance is a mild function of the letter-array dispersion. The closer the letters, the more will be reported.

6. Voluntary eye motion (horizontal) in connection with psychophysical experimentation with lineal patterns does not occur until at least 125 msec after the onset of the stimulus flash. The latency of such gross motions (greater than 1/2 deg) is a function of flash energy. Furthermore, postexposure motion is a function of the stimulus material in the exposure. Saccadic postexposure motion occurs for stimuli with numerals, while slow scanning characterizes the postexposure motion that occurs with pattern stimuli.

7. It has been demonstrated that proximity and containment enhance performance in the recall of related items (patterns); these same features interfere with the recall of

related items (patterns); these same features interfere with the recall of unrelated items--that is, zero-gram English letters. This principle, operative in a variety of situations, is considered to be a general performance characteristic.

8. The naive notion that performance always improves with increased exposure duration has been demonstrated to be false. Certain stimulus conditions result in nonmonotonically decreasing error for moderate exposure durations. Such conditions may be related to eye motion interactions, light-versus-time considerations, and other details of presentation.

6.2 A Line of Research

The approach to the problem of one-glance pattern recognition taken here differs from other studies in two respects. First, patterns physically larger than those ordinarily used have comprised the majority of a stimulus material. Second, the 9 x 12 pattern ensemble, which is used almost exclusively, is bigger than source ensembles discussed in the literature. These differences were incorporated at the outset in an attempt to come closer to the normal visual information-transmission problem of practical interest. The major visual problem is not the one-glance problem; rather, it is the two-, three-, four-glance problem at information sources of even greater extent than those used here. The transfer of information from glance to glance is a very significant attribute of visual performance. Having established some of the ground rules for the one-glance problem with dispersed patterns, one should now pursue the problem of information transmission between glances.

A direct empirical approach employing a combination of psychophysical and objective measurements, such as eye motion measurements, is adequate for the problem of multiple-glance recognition. Studies based essentially on sampling techniques in which the subject is allowed as many opportunities as he desires to reassess the stimulus information appear quite feasible; they represent very fruitful areas for continued work aimed at understanding, at least at the psychophysical level, the operation of the visual modality. The major problem in all this work is the design of experiments. One can often state what he is interested in measuring much better than he can measure it. Most of the interesting things to measure require detailed and ingenious experimentation. And this ingenuity is most conspicuous by its absence from the literature.

The role of short-term memory in vision is increasingly important in the study of the transfer of information from one to another glance. Even the simple problem of defining what time-duration constitutes a glance--that is, a discrete information intake interval--is a significant unanswered question. These problems have not yet been rigorously approached; they must be approached if we are to try to achieve an understanding of human utilization of visual information. Whereas many of the possibilities and variations of tachistoscopic presentation have been thoroughly investigated and in large measure have contributed to our present understanding of information in vision, sampling techniques have not been subject to the same degree of experimentation diversity. Appropriately designed sampling techniques will allow us to infer a great deal from direct empirical psychophysical measurement about the process of information utilization and processing other than through the intermediary of a second saturated response system. The major problem in these investigations is response time. Clearly, the human can take in information much faster than he can use it--at least when he is required to utilize it through behavior manifested by a response system different from the receiving modality.

It should not be necessary to spell out here the specific experiments that should be conducted to lend more meaning to this work, to relate it more closely to published studies, and to provide more significant or more general answers regarding the operation of the visual modality. In several places in the text, questions have been raised to which answers must exist. It is more important to relay the impression to the reader that, after considerable psychophysical experimentation in vision, the author's considered technical opinion is that this direct empirical psychophysical approach has not been fully exploited in visual information-transmission investigations. Quite clearly, it has not been completely exploited in this work either. While considerable interest and confidence are placed in other objective measures of performance, it is really behavioral or psychophysical measures of performance that determine the human's reaction to his environment.

Appendix A

A VISUAL AND A KINESTHETIC-TACTILE EXPERIMENT IN PATTERN RECOGNITION*

In sensory-aids research one is often concerned with a human subject's performance in a task for which the normal input sensory modality is replaced by an alternative modality. In addition to inherent differences in the information intake and processing capabilities of two sensory systems, there are in each system purely mechanical effects that significantly modify performance and thus complicate the problem of sensory replacement. The experiment reported here compares human performance in a simple pattern-recognition task with the visual and the kinesthetic-tactile sensory modalities. Such an experiment illustrates both the inherent information-processing capabilities and the mechanical factors that influence performance (1).

A.1. A Visual Experiment in Pattern Recognition

In the visual part of the experiment twenty-one subjects were shown a sequence of thirteen patterns, each consisting of a horizontal row of six black or white squares. Patterns were exposed with white signal boxes on a black background for six discrete time durations ranging from 30 to 500 msec. Subjects responded by placing X's on the answer sheet in each position where a white element appeared. The ambient light level was reasonably constant, and the stimulus intensity well above threshold. Figure A.1 shows sample patterns.

Performance in this task was good. An over-all error rate of 2.55 percent was noted for all patterns and all times. (An error was arbitrarily defined as any square mismarked either through omission of a correct response or insertion of an incorrect response.) The percentage of error versus exposure-time duration for all patterns and for the test group (three white squares out of six) is shown in Figure A.2. Figure A.3 shows the relative number of errors made on each of the thirteen test patterns. The ordinate scale is normalized to the number of errors on the pattern with the fewest errors. Figure A.4 shows the distribution of errors with respect to the stimulus positions. The stimulus patterns were so arranged that subjects would make approximately the same number of responses for each position for the whole experiment.

**The author gratefully acknowledges the contributions of Dr. J. C. Bliss in the work on the kinesthetic-tactile modality described in this appendix.*

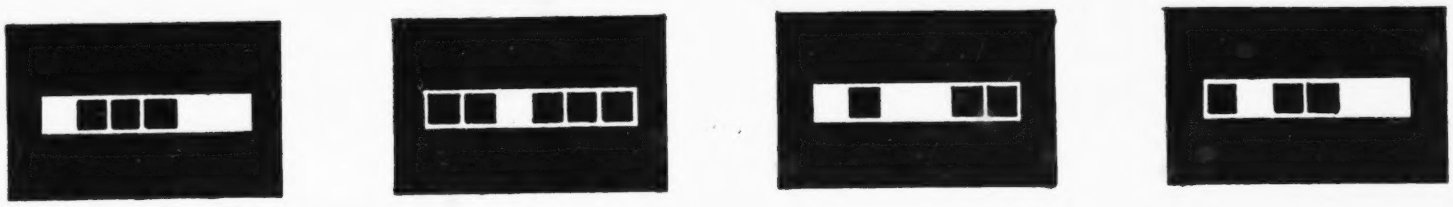

Figure A.1. Sample Patterns for Visual Experiment

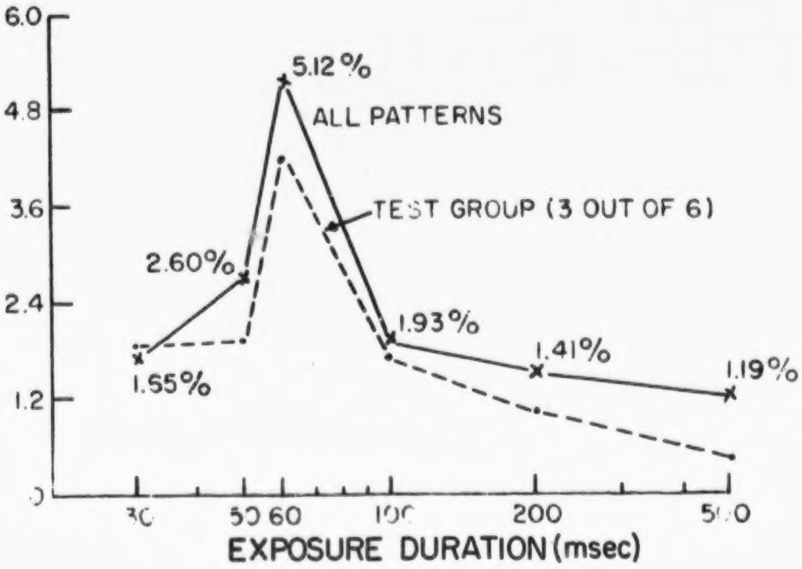

Figure A.2. Percentage of Error vs Stimulus Duration in the Visual Experiment

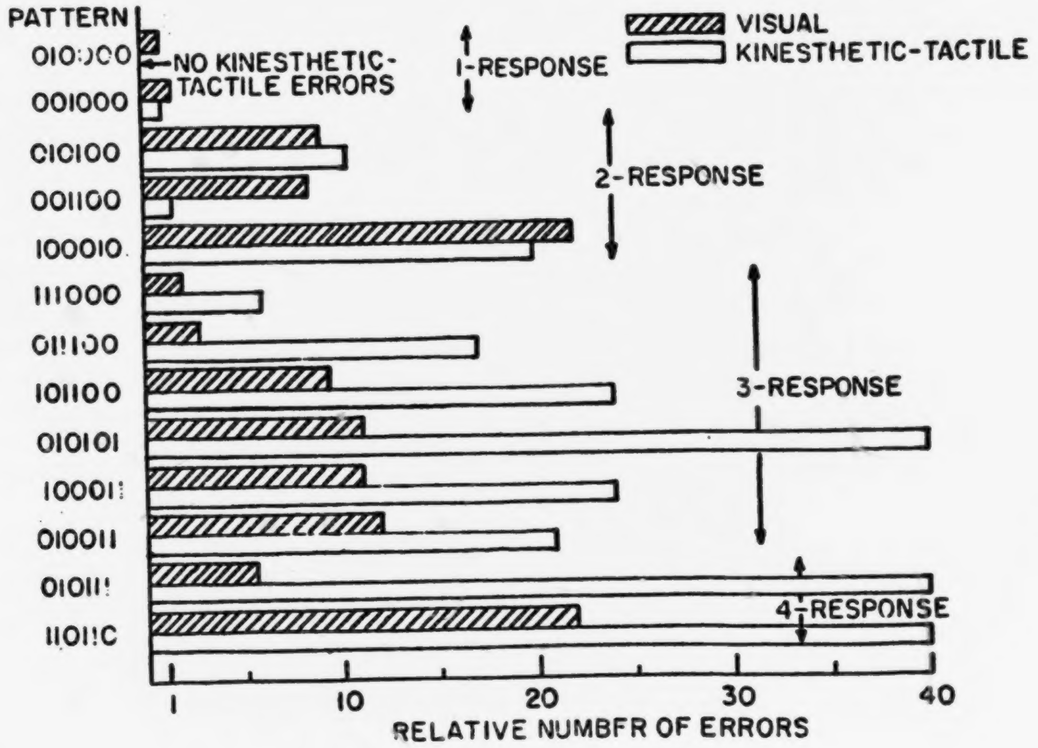

Figure A.3. Relative Number of Errors Between Patterns

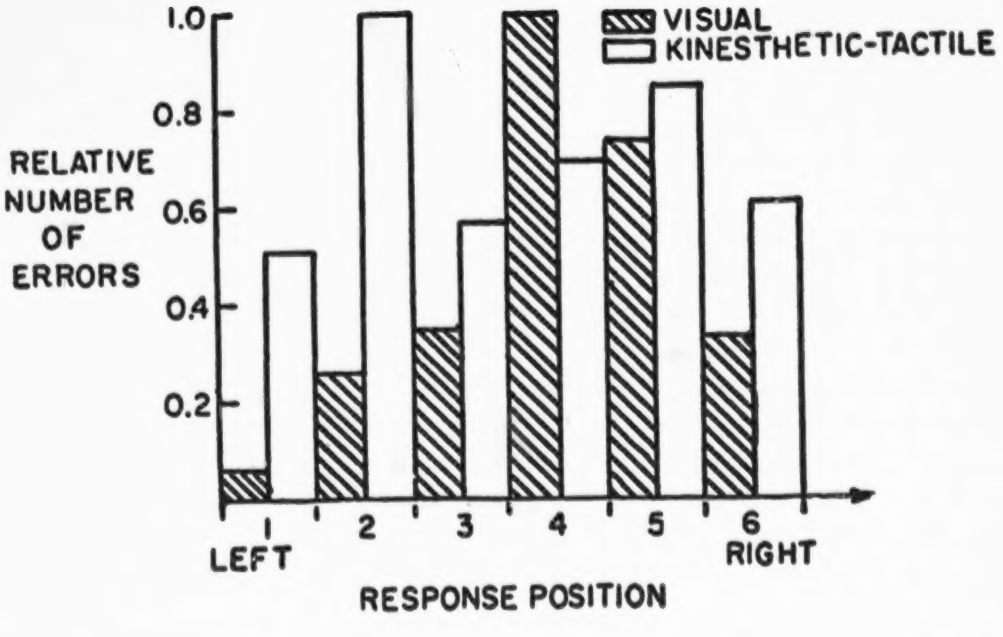

Figure A.4. Relative Number of Errors vs Response Position or Stimulated Finger

The most interesting feature of the results is the peak in the error-rate-versus-exposure-duration curve in the vicinity of 60-msec exposure time. This tendency is present in each individual pattern (at least when there is a sufficient number of errors to justify this statement). No definite explanation is offered for this phenomenon. However, the author has concluded (through introspection) that pattern exposures of approximately 60-msec duration produced the most pronounced afterimage. Furthermore, it is more difficult to stabilize the position of the afterimage in the visual field for exposures of this duration than for any other exposure time used in the experiment. (This peak in error rate was not noted in the kinesthetic-tactile experiment.)

For a 100-msec exposure of patterns from the test group the subjects received information at a rate of less than 30 bits/sec, and their response was essentially errorless (1.9 percent). The curve in Figure A.2 indicates that the subjects who took this test were capable of an information intake of approximately 90 bits/sec with the same error rate for much shorter exposure times (30 msec). (Not all subjects respond in this manner. Some made virtually no errors during the whole experiment.)

Figure A.3 illustrates how the errors were distributed for the patterns presented. Note that the positions of the white squares in the pattern are indicated by "1." Despite the fact that a pattern of two white squares and four black squares might be considered informationally equivalent to its complement (four white squares and two black squares), higher error rates are noted in patterns in which the subject's response is "four X's." In the three-out-of-six response patterns the situation is different because both complementary pairs require the same number of responses. Patterns 7 and 10 are complements, yet the error rate for 10 is three times higher. Examination of the patterns shows that the three-in-a-row response pattern of 7 is probably much simpler to encode than the separated response pattern of 10. Patterns 8 and 11 are also complements/ the same error rate and general characteristics of the response pattern are noted. This phenomenon supports the general conclusion that informationally equivalent tasks are not always psychophysically equivalent.

Referring again to Figure A.4, the fact that fewer errors are shown for the subjects in positions 1 and 6 is in general agreement with many published results. The preponderance of errors in position 4, despite the fact that in general, the subjects' eyes were fixated on this position, is more difficult to explain. This differs from results published by Averbach and Coriell (2) in a study of short-term memory in vision. They report that when the subject is able to assimilate information from a linear array for a fixed time duration, he makes the fewest number of "recall" errors in the central positions. The difference is explained in section 5.4.

A.2. Kinesthetic-Tactile Experiment in Pattern Recognition

The kinesthetic-tactile experiment consisted of simultaneously moving some combination of the subject's fingers with an external driving mechanism. Only six fingers were used: the index, middle, and fourth fingers of each hand. The various combinations of finger movements corresponded to the thirteen black-and-white 1 x 6 matrix patterns used in the visual part of the experiment. The apparatus consisted of eight finger rests, six of which were connected and could be moved in the vertical direction by Sylphon bellows according to a program punched on paper tape. The movements were at least 1/8 in. in all cases, which is well above threshold (3). Figure A.5 shows the apparatus and the air valve which used punched-paper tape as the slide. A shield was so placed that the subject could not see his hands during the experiment. On it there was a diagram that gave the number labels for the six fingers which were numbered 1 through 6, from left to right. Six discrete time durations, during which air pressure was on the bellows, covered the range from 10 to 500 msec. The subject responded orally by indicating the numbers of the fingers that were moved.

The combined error rate for all times and all patterns was 10.5 percent. (An error is defined as either reporting a finger movement that did not occur or failing to report a finger movement.) The percentage of error versus exposure-time duration for the test group of patterns is given in Figure A.6.

Figure A.4 shows the distribution of errors with respect to the finger stimulated. This distribution can be explained if one assumes that most errors in finger localization are made between adjacent fingers of the same hand. This assumption was checked in an auxiliary experiment in which all combinations of the 2-out-of-6 patterns were presented to two subjects. Table A.1 shows the confusion matrix obtained for the errors. Thus, the relatively low error rate obtained for fingers 3 and 4 (Figure A.4) is probably due to the fact that they are on different hands, and the low rate for fingers 1 and 6 probably results from the fact that these were the "outside" fingers in the experiment.

Table A.1

Stimulus-Response Matrix for all Combinations of Two-Out-of-Six Finger Movements

RESPONSE

STIMULUS	1	2	3	4	5	6
1	38	1	1			
2	4	24	11		1	
3		7	33			
4				30	10	
5				2	35	3
6					3	37

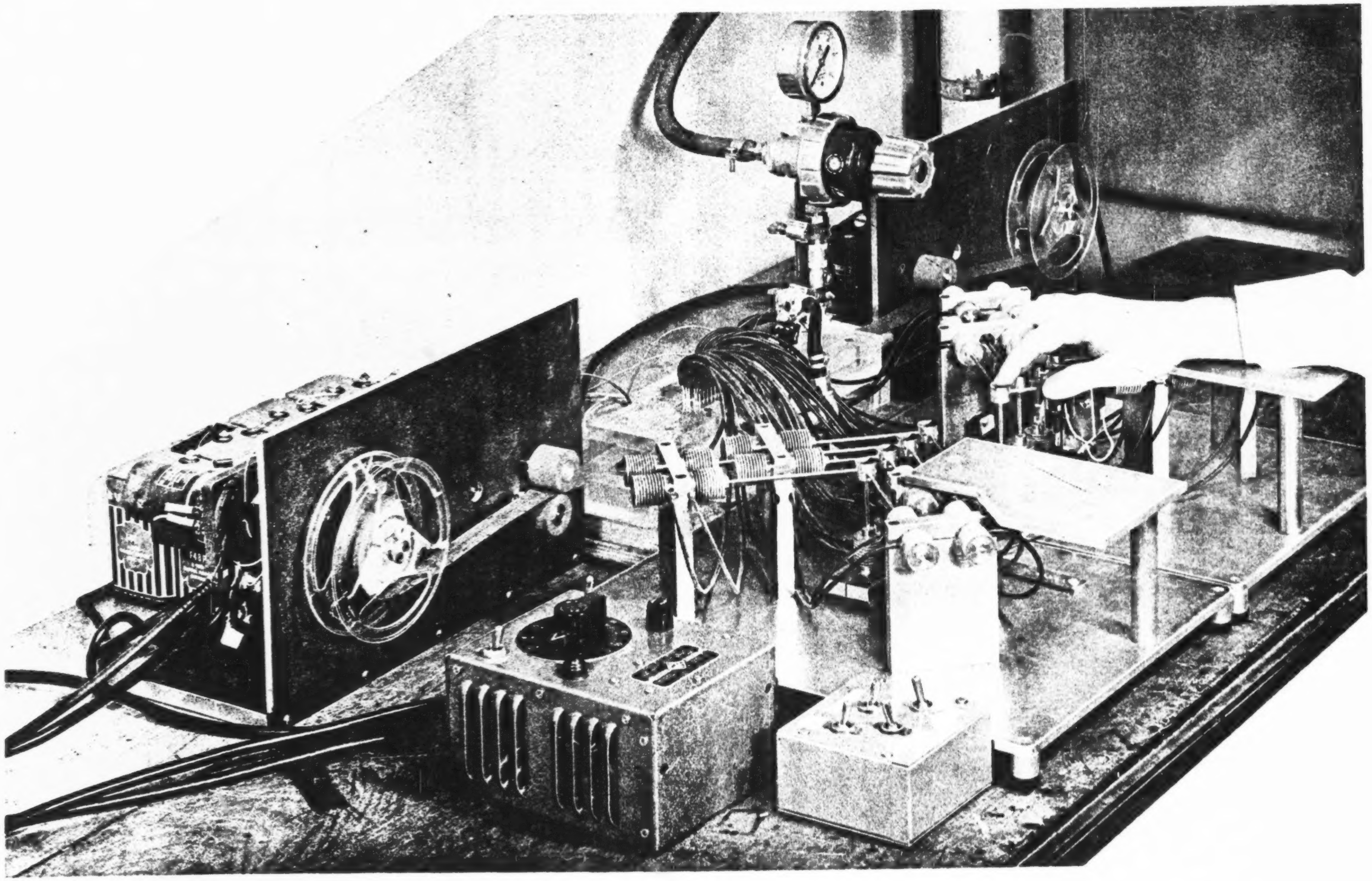

Figure A.5. Air-Driven Finger Stimulator

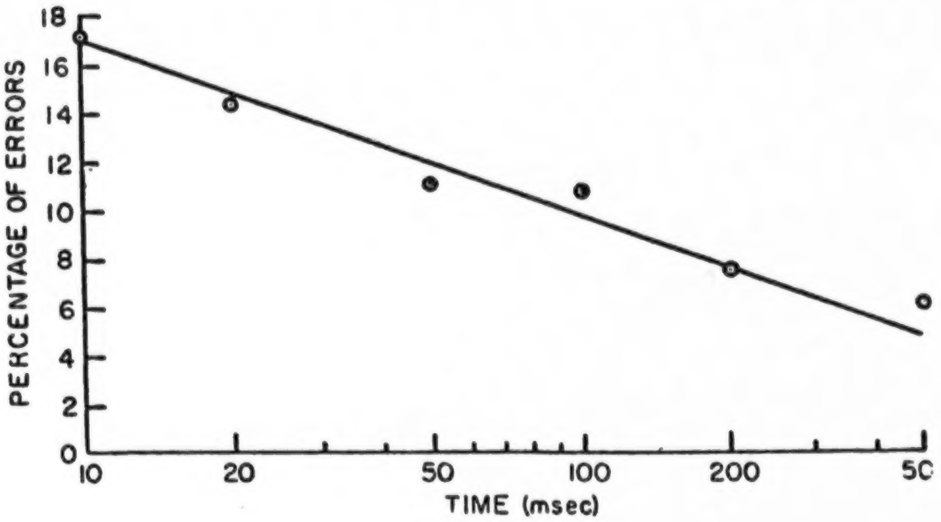

Figure A.6. Percentage of Error vs Exposure Time for Test Patterns in the Kinesthetic-Tactile Experiment

Figure A.3 shows the relative number of errors made on each of the thirteen patterns. The percentage of error increased markedly with the number of fingers stimulated. Complementary patterns with unequal numbers of fingers stimulated apparently give significantly different error rates. Patterns in which the stimulated fingers were adjacent--for example, 111000--resulted in a much lower error rate than patterns in which alternate fingers were stimulated--for example, 010101.

A.3. Comparison of Visual and Kinesthetic-Tactile Results

Because the stimulus intensities for each modality were well above threshold intensities (although no attempt was made to equate the stimulus energy for each modality), it can be concluded that all subjects perform much better in the task when visual information intake is used. Error rates are an order of magnitude higher for the kinesthetic-tactile experiment.

The assumption that complementary patterns are informationally equivalent is not upheld by the results for visual or kinesthetic-tactile stimulations. However, the reasons are different. When the visual observer is asked to note and report the positions of the white squares, he does not appear to encode the pattern as a whole, but rather to "measure" the distance between stimulus squares. This results in higher error rates on the complementary patterns with the greater distance between response positions. (See patterns 7 and 10, Fig. A.3.)

With tactile stimulation, complementary excitation (movement-no movement) appears to be even less useful as an encoding tool for the subject. This can be seen from the marked increase in error rate as one goes from one to four stimuli out of six (Figure A.3).

In kinesthetic-tactile stimulation the ability to dichotomize the stimulus because of the use of two hands results in position errors for the two modalities that are significantly different in positions 3 and 4. In the visual display the center positions are most often confused because the subject presumably measures distance from the end. This conclusion is borne out in both the position-error curve (Fig. A.4) and the pattern-error curve (Fig. A.3).

A simple model of visual information transmission which assumes that performance should continue to improve as the stimulus duration is increased (because of greater stimulus energy at constant intensity) is not consistent with data for the visual sense. The sudden increase in error rate when 60-msec exposure times are used, which probably results from some "mechanical" aspect of the visual process, is not present in the tactile experiment. The error characteristic in Figure A.2 is quite similar to the brightness-judgment-versus-duration curves for constant brightness pulses which manifest the Broca-Sulzer phenomenon (4, 5). Perhaps the higher apparent brightness of the 60-msec exposure produces the more pronounced afterimage observed at this duration.

The results and conclusions presented in this report are preliminary. No special significance is attached to the numerical results; they are considered to be illustrative.

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Appendix B

COMPILATION OF EXPERIMENTAL DATA

Data are presented in the order in which the various experiments are discussed in the text.

Experiment 1

Table B.1 indicates the random-structured grouping made by each of the twenty subjects.

Experiment 2

Tables B.2 and B.3 summarize the best-fit and absolute registration grades for each of seven subjects. Blank spaces indicate discarded data; a hyphen indicates that the subject missed the exposure because of inattention and the like.

Experiments 3 and 3A

Table B.4 indicates the number of letters reported correctly by each of six subjects. Data are compiled by pattern, with increased duration for each pattern running from top to bottom. Durations used were 1, 2, 5, 10, 20, and 50 frames.

The data in the right-hand column are from Experiment 3A. Scores with redundant letter groups are underlined. The other scores are for the same letter groups as those used in the left-hand column. This group of figures is included to indicate the repeatability of the experiment.

Experiment 4

Table B.5 presents a compilation of experimental data for the three subjects tested in Experiment 4. All pattern and sample pair exposures lasted ten frames; the duration data in Table B.5 refer to the delay between pattern and sample pair exposures. The number of pairs correctly grades (out of ten) are given in the last three columns.

Experiment 5

Experimental data for six subjects with two lineal arrays (A and B) of letters are shown in Table B.6. The two figures at each duration are the number of letters reported from two different exposures with different letters.

Table B.1

Experiment 1—Data

Pattern	KK	JOB*	JHS	UFG*	HG	WB	LCM*	JB	RL	DET	AMS	HS	AM	RWC	SMS	RAS	HG	PD	ASB	HG	*Structured*	*Random*
1	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	20	0
2	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	0	20
3	R	S	S	R	R	S	S	R	R	S	R	R	R	R	R	S	R	R	R	S	7	13
4	S	S	S	S	R	R	S	S	S	S	S	S	R	S	R	S	S	S	R	S	15	5
5	S	S	S	S	S	S	S	S	S	S	S	R	R	R	R	S	R	S	S	S	15	5
6	R	R	S	R	R	R	R	S	R	S	R	S	R	S	R	S	R	R	R	R	6	14
7	S	S	S	S	S	S	R	S	S	S	S	S	R	S	S	S	R	S	R	S	16	4
8	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	20	0
9	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	20	0
10	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	S	R	R	R	1	19
A	S	S	S	S	S	S	S	S	S	S	R	S	R	S	R	S	R	S	R	S	15	5
B	R	S	R	R	R	R	R	S	R	R	R	S	R	R	R	R	R	S	R	S	5	15
C	S	R	R	R	R	R	S	S	S	R	S	R	R	R	R	S	S	R	R	S	8	12
D	R	R	R	R	R	R	R	R	R	S	R	S	R	S	R	R	R	S	S	S	6	14
E	S	R	R	S	S	R	S	S	S	R	R	R	R	S	S	S	R	S	S	R	11	9
F	S	R	S	S	S	R	R	S	S	R	R	S	R	S	S	S	R	S	R	S	12	8
G	S	S	S	S	R	S	S	S	S	S	S	S	R	S	S	S	R	S	S	S	17	3
H	S	S	S	S	S	S	S	S	S	R	S	S	R	S	S	S	S	S	S	S	18	2
I	R	R	S	R	R	R	R	S	R	R	R	S	S	R	R	R	R	R	S	S	6	14
J	S	S	S	S	S	S	S	S	S	S	S	S	R	S	S	S	S	S	S	S	19	1

*Experiment 2 subject.

Table B.2

Experiment 2—(5)-Patterns Performance Scores

Pattern Designation	1		2		5		10		20		50	
	A	B	A	B	A	B	A	B	A	B	A	B
(A)	033 011 23	333 211 23	201 002 10	211 022 12	043 043 3-	243 243 4-	430 004 43	432 144 43	044 043 23	244 244 43	413 003 13	443 343 54
(B)	001 301 20	111 302 21	010 000 00	221 202 02	0-2 410 01	1-2 412 22	201 001 21	221 424 23	010 120 32	332 223 33	010 132 10	231 434 42
(C)	212 200 21	222 221 32	32- 021 20	32- 232 22	021 010 01	333 223 22	213 012 -2	323 123 -4	202 210 24	304 224 34	023 220 10	335 443 34
(D)			301 100 0	332 103 0	210 010 10	434 134 22	133 111 02	433 242 23	030 203 13	533 333 34	1 1 020 30	4 2 142 43
(H)	011 021 11	321 344 32	130 012 21	430 343 33	-32 12	-42 24	031 003 01	431 454 41	134 -31 -3	544 -34 -4	515 531 32	545 534 54
(F)	011 210 11	222 212 31	020 -10 0-	232 -13 2-	001 112 10	354 334 52	322 332 10	344 435 52	020 010 10	543 515 53	231 233 -0	355 435 -3
(G)	000 000 -0	012 244 -2	200 023 00	201 123 03	210 324 10	233 334 43	110 300 40	444 354 43	211 300 0-	243 355 5-	104 300 5-	445 345 5-
(E)	200 010 10	412 233 12			013 0-2 12	433 2-3 32	020 210 -0	244 222 -0	302 020 22	444 420 42	302 410 33	352 532 33
(I)	000 000 0-	121 020 0-			011 000 00	212 100 21	000 010 00	210 030 12	100 000 1	221 020 2-	200 000 0-	423 330 2-
(J)	302 002 00	444 152 25			22- 100 00	54- 244 45	230 302 0-	545 354 4-	310 300 00	545 354 35	352 200 35	354 245 45

A = absolute registration grade.
B = best-fit grade.

Table B.3

Experiment 2—(10)-Patterns Performance Scores

Pattern Designation	1		2		5		10		20		50	
	A	B	A	B	A	B	A	B	A	B	A	B
(1)	4 4 6	6 6 6	3 3 3	3 6 3	1 8 3	3 8 6	1 8 6	3 8 6	5 0 10	5 10 10	1 8 10	1 8 10
	0 1 0	2 1 10	- 0 9	- 7 9	2 6 10	4 6 10	4 10 10	6 10 10	5 10 0	5 10 10	2 4 4	6 4 9
	4 0	4 0	0 0	4 0	5 3	5 8	10 1	10 6	0 3	10 6	10 0	10 8
(2)	0 3 0	4 3 0	0 3 0	3 3 0	2 - 2	4 - 3	4 1 2	4 4 3	2 1 2	3 3 3	4 2 2	5 5 4
	0 0 3	0 3 3	1 2 0	1 3 2	2 - 2	3 - 2	2 3 2	4 4 2	0 3 2	3 4 2	2 3 3	3 3 3
	0 1	0 1	2 1	3 3	3 -	5 -	1 2	4 3	2 3	3 3	3 3	5 4
(3)	0 0 3	4 4 6			0 0 3	4 6 4	0 4 0	6 6 4	2 0 0	2 7 6	0 5 6	7 6 8
	0 5 3	3 5 6			0 6 3	4 6 4	0 0 2	6 6 7	0 6 1	2 7 7	0 0 3	6 7 8
	2 3	2 6			0 0	1 5	0 4	2 5	2 3	2 4	0 2	1 7
(4)	5 2 0	7 6 0	2 2 1	5 6 3	3 2 3	5 6 5	3 2 5	9 7 6	1 3 2	8 6 5	7 2 2	8 9 5
	3 2 1	3 3 4	2 0 1	4 0 2	4 3 2	4 5 4	0 3 0	4 6 6	2 3 3	4 5 6	3 6 0	3 7 4
	0 0	2 0	4 1	5 2	4 0	7 0	2 3	7 3	4 3	7 3	3 2	9 4
(5)	0 2 4	4 4 4	4 2 0	4 5 5	2 0 0	2 0 5	- 2 5	- 6 6	2 5 6	5 5 6	1 6 0	1 7 6
	1 0 3	1 6 5	4 0	4 6	2 0 1	2 5 6	0 0 -	2 6 -	3 7 2	5 8 6	0 3 7	6 6 9
	0 2	1 4	- 2	- 5	0 2	5 6	0 2	1 6	- 5	- 5	7 0	7 7
(6)	0 0 0	2 0 0	3 3 1	3 4 2	1 2 1	4 3 2	3 0 0	5 4 3	3 0 0	6 4 3	1 0 0	7 3 3
	0 0 0	0 0 0	0 0 1	0 0 2	1 4 0	1 7 0	2 2 1	5 3 1	2 5 1	3 6 1	3 4 0	3 7 2
	0 0	0 0	2 0	2 2	2 0	4 0	1 3	3 3	3 3	5 3	4 3	5 3
(7)	3 4 1	3 4 3	6 2 2	6 6 5	6 6 2	6 7 6	6 6 1	6 6 5	6 7 2	6 7 7	1 6 2	4 8 7
	2 4 1	4 4 6	2 2	3 7	5 4 2	5 4 6	6 7 3	6 7 6	6 2 6	6 6 6	6 8 2	8 9 8
	4 2	4 5	5 1	5 6	6 2	6 7	6 6	6 7	4 6	6 6	- 6	- 7
(8)	2 0 0	6 2 1	3 0 0	6 5 3	8 3 5	8 6 5	3 6 3	10 9 6	3 3 3	9 10 7	6 - 3	10 - 8
	5 3 3	5 5 3	0 0 3	3 3 3	3 3 3	6 8 3	- 6 4	- 8 4	3 3 3	10 9 7	9 10 3	9 10 3
	3 3	3 3	0 2	3 3	3 3	5 3	3 3	3 6	6 7	8 7	6 3	6 7
(9)	4 4 8	5 6 8	5 0 8	5 0 8	8 3 7	8 5 7	7 3 2	7 7 8	2 2 8	5 7 8	- 8 10	- 8 10
	5 4 4	5 10 8	4 2 2	5 10 8	3 4 5	4 8 8	4 10 7	4 10 7	3 9 4	5 9 8	8 2 4	8 10 10
	3 4	7 8	0 4	0 4	5 6	9 6	10 2	10 8	9 8	9 8	10 1	10 7
(10)	0 0 1	1 0 1	0 - 0	0 - 0	0 0 1	2 1 2	0 2 1	3 4 2	0 1 0	4 3 2	2 1 1	5 4 4
	0 0 1	0 0 1	0 0 1	0 0 1	0 0 1	0 0 1	1 1 1	1 2 1	1 0 1	2 4 2	2 2 0	5 4 3
	0 0	0 0	2 0	4 1	1 0	3 2	0 3	2 3	1 4	2 4	0 2	4 4

A = absolute registration grade.
B = best-fit grade.

Table B.4

Experiments 3 and 3A—Data

Run Number (1, 2, 3) Practice	Pattern	Experiment 3 Number Correct by Subject							Experiment 3A		
		DJK	RJK	LCM	JJJ	CEK	MAP	Totals (6)	RJM	LCM	JJJ
6	H	1	3	2	1	4	4	15			
19	H	4	4	3	4	3	5	23			
28	H	2	5	2	3	2	4	18			
14	H	2	5	2	3	3	5	20			
42	H	5	4	4	5	4	5	27	5	4	5
31	H	5	5	5	5	5	5	30			
9	J	0	3	1	2	-	3	9			
4	J	1	3	1	2	4	2	13	3	3	2
26	J	3	4	-	-	-	5	12			
36	J	5	5	3	4	5	5	27			
33	J	5	5	3	5	5	5	28	5	5	5
22	J	5	5	5	4	5	5	29			
15	B	1	2	1	2	2	3	11			
30	B	2	3	-	2	2	3	12			
23	B	3	5	2	2	4	5	21			
5	B	3	5	4	4	5	5	26			
40	B	5	5	5	5	5	5	30	5	5	5
18	B	5	5	5	5	5	5	30			
35	(1)	1	1	1	0	1	3	7			
24	(1)	3	5	2	3	3	4	20			
12	(1)	3	5	3	3	-	2	14	4	2	3
16	(1)	3	5	3	4	4	4	23			
44	(1)	7	6	3	4	5	7	32	7	4	5
7	(1)	6	9	5	4	5	8	37	7	5	6
43	(2)	2	2	2	3	-	3	12	3	1	2
39	(2)	1	2	3	2	2	4	14			
21	(2)	2	3	2	2	3	4	16			
45	(2)	2	4	3	3	3	5	20	4	3	4
8	(2)	4	5	4	5	5	5	28			
13	(2)	6	4	6	3	4	5	28			
20	(6)	-	3	0	-	3	3	9			
38	(6)	1	3	1	1	4	3	13			
27	(6)	3	3	-	-	2	3	11			
10	(6)	4	5	3	3	2	-	17	4	3	3
17	(6)	1	5	4	4	5	4	22	5	4	4
34	(6)	7	6	5	4	7	9	38			
32	(8)	1	3	2	2	3	4	15			
29	(8)	1	2	1	3	3	4	14			
37	(8)	3	4	3	2	3	4	19			
41	(8)	2	3	3	3	2	4	17	3	3	5
11	(8)	4	6	5	5	4	7	31			
25	(8)	6	7	5	5	8	6	37			

Table B.5

Experiment 4—Data

Pattern	*Delay Duration*	Subject		
		RJM	*LCM*	*AMS*
F	1	(9)*	(7)	(8)
F	10	(9)	(7)	(7)
F	20	(9)	(8)	(8)
B	1	(9)	(9)	(8)
B	2	(9)	(8)	(7)
B	5	(10)	(6)	(9)
B	10	(10)	(7)	(5)
B	20	(8)	(5)	(8)
J	1	(10)	(10)	(10)
J	2	(10)	(10)	(10)
J	5	(9)	(8)	(8)
J	10	(10)	(10)	(10)
J	20	(10)	(10)	(10)
6	1	(6)	(7)	(5)
6	2	(6)	(3)	(6)
6	5	(7)	(2)	(5)
6	10	(4)	(5)	(3)
6	20	(4)	(1)	(5)
8	1	(9)	(7)	(7)
8	2	(9)	(7)	(8)
8	5	(8)	(7)	(9)
8	10	(8)	(9)	(9)
8	20	(9)	(7)	(8)
3	1	(6)	(5)	(6/9)
3	10	(8)	(9)	(7)
3	20	(5)	(6)	(7)
10	1	(8)	(4)	(6)
10	10	(7)	(5)	(4)
10	20	(6)	(6)	(3)

*Number of correctly related samples (out of ten).

Table B.6

Experiment 5—Data

			Experiment 5A						
	Run No.	*Duration*	*RJM*	*LCM*	*JJJ*	*JJ*	*RWF*	*MF*	*Six Subject Average Letter/ Exposure*
Sequence A	7	(1)	5	-	-	2	2	2	2.8
	14		4	-	2	2	4	2	
	5	(2)	5	1	3	2	4	2	3.2
	12		5	4	2	3	4	3	
	4	(5)	5	2	3	3	5	3	3.4
	11		5	2	2	3	4	4	
	9	(10)	6	2	3	0	6	5	4.0
	13		5	4	3	4	6	5	
	8	(20)	5	5	5	5	7	5	4.8
	15		5	3	3	5	5	5	
	6	(50)	6	6	5	7	6	10	6.6
	10		7	4	5	5	10	9	
					Experiment 5B				
Sequence B	7	(1)	5	4	3	1	1	1	2.5
	14		4	1	3	2	1	4	
	5	(2)	5	2	1	4	5	5	3.5
	12		5	3	3	2	4	3	
	4	(5)	5	4	3	4	5	4	4.1
	11		5	3	-	3	4	5	
	9	(10)	5	3	4	4	4	5	4.1
	13		5	2	2	5	7	3	
	8	(20)	5	5	5	5	6	2	4.8
	15		5	5	5	5	5	5	
	6	(50)	6	4	5	6	5	3	5.2
	10		5	6	5	5	7	5	

Experiment 6

Table B.7 is a compilation of experimental data for the ten subjects. The upper row of figures for each duration-distance value is the number of counts reported for the high-count run. The lower row is from the low-count run.

Experiments C1—C4

Data on which the results of experiments described in Appendix C are based are recorded in Tables B.8, B.9, and B.10. The experimental data refer to the number of errors made by the subjects as a function of position in the 1 x 6 matrix and exposure duration. Data for Experiment C-3 are not tabulated.

Table B.7

Experiment 6—Data

	Run Number	Distance	RJM	LCM	JJ	JB	WJM^c	UFG	OT	JJJ	WSB	JGB	(10) Totals	Percent Average/ Run
T = 1	4	(1)	2	0	3	0	0	0	0	0	0	4	(20)	10
	8		0	2	0	2	1	0	0	1	2	3		
	24	(2)	2	0	3	1	1	0	0	2	1	4	(20)	10
	30		1	0	0	1	0	0	0	2	0	2		
	6	(5)	2	0	0	0	1	0	0	1	2	2	(12)	6
	3		1	0	2	0	0	0	0	0	1	0		
	20	(10)	1	0	1	0	0	0	0	1	0	1	(5)	2.5
	27		0	0	1	0	0	0	0	0	0	0		
T = 2	26	(1)	6	3	5	4	2	3	5	4	4	4	(56)	28
	18		2	2	2	1	0	1	0	1	2	5		
	10	(2)	3	5	4	3	1	0	0	3	4	4	(43)	21.5
	5		3	3	2	1	0	0	1	2	1	4		
	17	(5)	3	0	2	2	0	0	0	2	3	4	(28)	15.5
	13		2	4	3	1	0	0	0	2	-	-		
	32	(10)	2	3	3	1	1	0	0	1	6	0	(17)	8.5
	21		0	0	0	0	0	0	0	0	0	0		
T = 5	25	(1)	12	11	12	7	8	7	9	7	9	12	(128)	64
	1		5	4	4	2	3	1	2	3	4	6		
	11	(2)	12	11	11	8	7	12	10	8	9	13	(147)	74
	29		5	6	6	5	2	4	3	5	5	5		
	31	(5)	9	10	7	5	3	6	4	7	8	6	(114)	57
	12		6	8	6	4	1	3	4	5	6	6		
	9	(10)	5	6	3	4	4	5	1	3	7	7	(66)	33
	15		4	4	1	2	1	2	0	1	4	2		
T = 10	28	(1)	11	11	11	10	11	12	10	11	11	11	(197)	98
	16		9	9	10	8	9	9	9	9	9	9		
	2	(2)	15	13	15	12	13	15	12	-	14	13	(172)	93
	14		5	5	5	4	5	5	5	6	5	5		
	22	(5)	15	15	15	11	11	14	17	12	15	14	(189)	96
	19		5	6	6	3	5	5	4	5	5	5		
	7	(10)	9	10	8	6	7	10	6	6	11	5	(153)	77
	23		9	7	8	7	7	7	7	7	8	8		

Table B.8

Experiment C-1—Data

Error Versus Duration

	Subjects								
Duration	*HG*	*TN*	*AS*	*BD*	*KK*	*JCB*	*OT*	*RNS*	*Totals*
No. 1 (30 msec)	0	2	0	0	0	0	0	1	3
No. 2 (50 msec)	3	2	0	0	3	0	1	3	12
No. 3 (60 msec)	3	3	1	6	2	0	0	2	17
No. 4 (100 msec)	5	2	2	3	3	4	3	2	24
No. 5 (200 msec)	1	0	0	2	0	0	0	0	3
No. 6 (500 msec)	0	6	1	5	0	4	0	0	16
TOTALS	12	15	4	16	8	8	4	8	75

8 × 6 × 6 × 13 = 3744 % error = 75/3744 = 2.0%

Error Versus Position

	(Bottom)				*(Top)*
Duration	1	2	3	4	5	6
No. 1 (30 msec)	0	2	1	0	0	0
No. 2 (50 msec)	0	5	3	2	2	0
No. 3 (60 msec)	2	8	5	1	1	0
No. 4 (100 msec)	4	9	6	4	1	0
No. 5 (200 msec)	0	1	1	1	0	0
No. 6 (500 msec)	2	4	4	1	3	2
TOTALS	8	29	20	9	7	2

Table B.9

Experiment C-2—Data

	Error Versus Position (9 Subjects)						
Duration	1	2	3	4	5	6	*Totals*
30 msec	0	0	0	3	3	1	7
50 msec	1	1	2	5	5	0	14
60 msec	0	1	0	4	4	2	11
100 msec	1	1	0	1	1	0	4
200 msec	0	1	1	0	0	0	2
500 msec	0	0	0	1	2	0	3
TOTALS	2	4	3	14	15	3	41

% error = 41/4212 = 0.96%

Note: Data were not compiled by subject when the experiments were performed.

Table B.10

Experiment C-4—Data

	Error Versus Position (5 Subjects)						
Duration	1	2	3	4	5	6	*Totals*
30 msec	0	1	2	1	3	2	9
50 msec	0	1	2	2	3	1	9
60 msec	0	0	1	1	3	3	8
100 msec	2	4	5	2	4	3	20
200 msec	0	2	2	0	1	1	6
500 msec	0	0	1	2	3	2	8
TOTALS	2	8	13	8	17	12	60

% error = 60/2340 = 2.55%

Note: Data were not compiled by subject when the experiment was performed.

Appendix C

SOME FURTHER EXPERIMENTS IN PATTERN RECOGNITION FROM LINEAR ARRAYS

Several experiments in addition to those described in Appendix A were performed with the 1 x 6 array. Appendix A experiments used a white-on-black array--that is, a black surround on which white squares and a white matrix border were superimposed (see Fig. A.1). Thus, in typical tachistocope presentations a black preexposure field (ambient room light) is followed by a predominantly black exposure and black postexposure field. This form of presentation is generally less conducive to persisting afterimages (from which information may be drawn, presumably) than the black preexposure field followed by a predominantly white exposure and black postexposure field (1). To assess the extent to which afterimage formation may cause the peak in error rate for 60-msec exposures (see Fig. A.2), three experiments with black-on-white linear 1 x 6 arrays were performed. Results plus a pattern-recognition experiment with a vertical white-on-black 1 x 6 array are the subject of this appendix.

C.1. Vertical Orientation of the Linear Array

To compare performance versus duration and position versus error-count data for the horizontal orientation of a white-on-black 1 x 6 array (Figs. A.2 and A.4) with the results obtained for vertical orientation of the array, the following experiment was performed. Eight subjects were exposed to the pattern array shown in Figure C.1 for durations of 30, 50, 60, 100, 200, and 500 msec and instructed to mark X's in the positions of the white squares on a similar matrix appearing on the answer sheet. Thirteen different patterns were exposed at each duration. A standard projection tachistoscope was used. Experimental conditions were as in the visual experiments described in Appendix A.

Figure C.3 shows the percentage of error* averaged over all subjects as a function of exposure duration for Experiment C-1. The over-all percentage of error was 2 percent, slightly less than the over-all percentage (2.55 percent) measured in experiments with a horizontally oriented array (see Appendix A). The same peak in error is noted, but the maximum error occurs at 100-msec durations rather than 60-msec durations. Furthermore, the error-versus-position histogram in Figure C.2 exhibits the same qualitative behavior as do the error-versus-position data

An error has been arbitrarily defined as any square mismarked either through omission of a correct response or insertion of an incorrect response (the same criterion used in Appendix A).

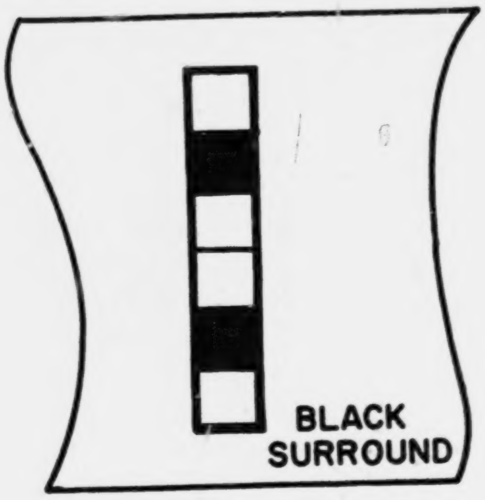
BLACK SURROUND
NOTE:
BLACK AND WHITE
ARE REVERSED IN
ACTUAL PRESENTATION

Figure C.1. Vertically Oriented 1 × 6 Array

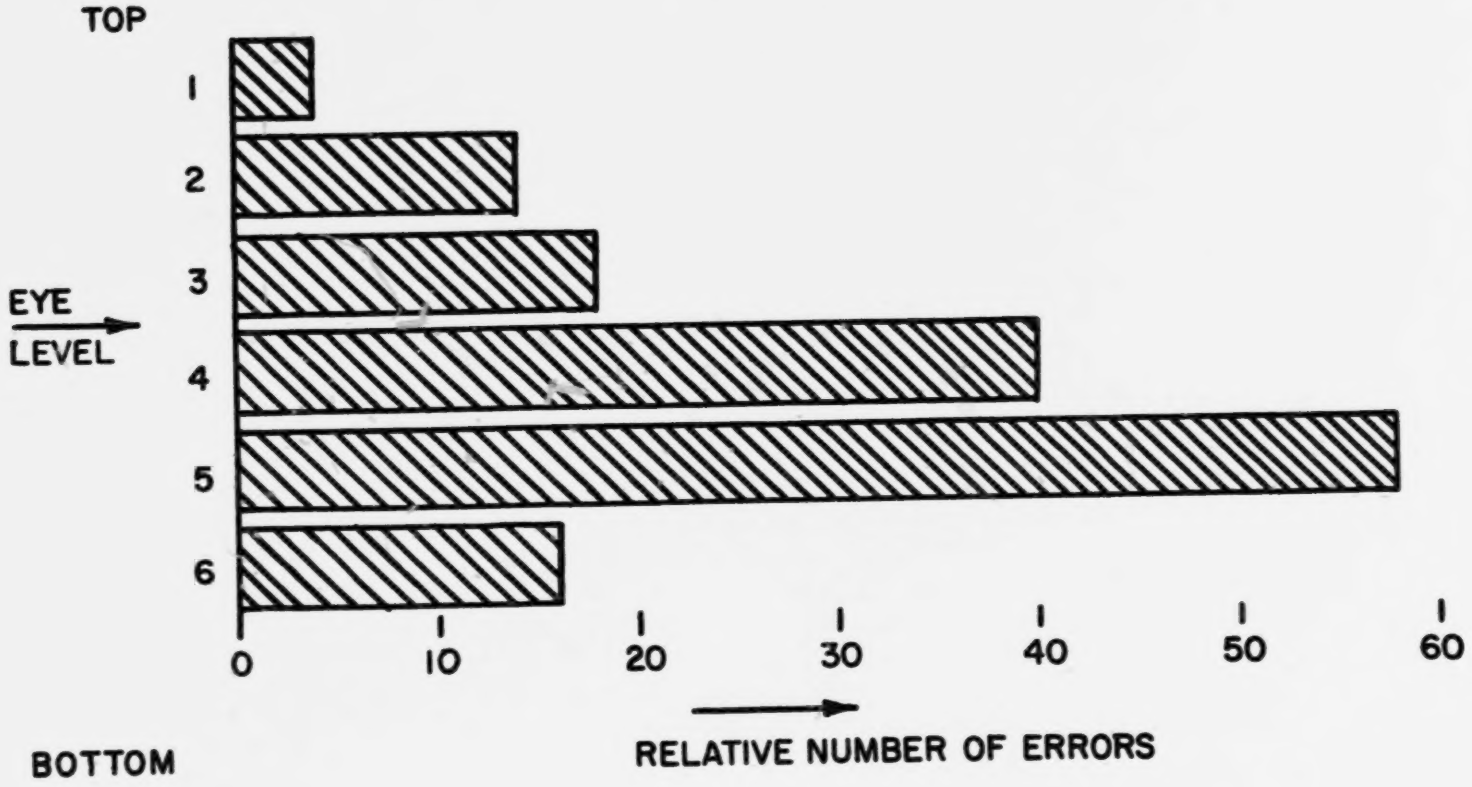

Figure C.2. Relative Error vs Position--Vertical 1 × 6 Array

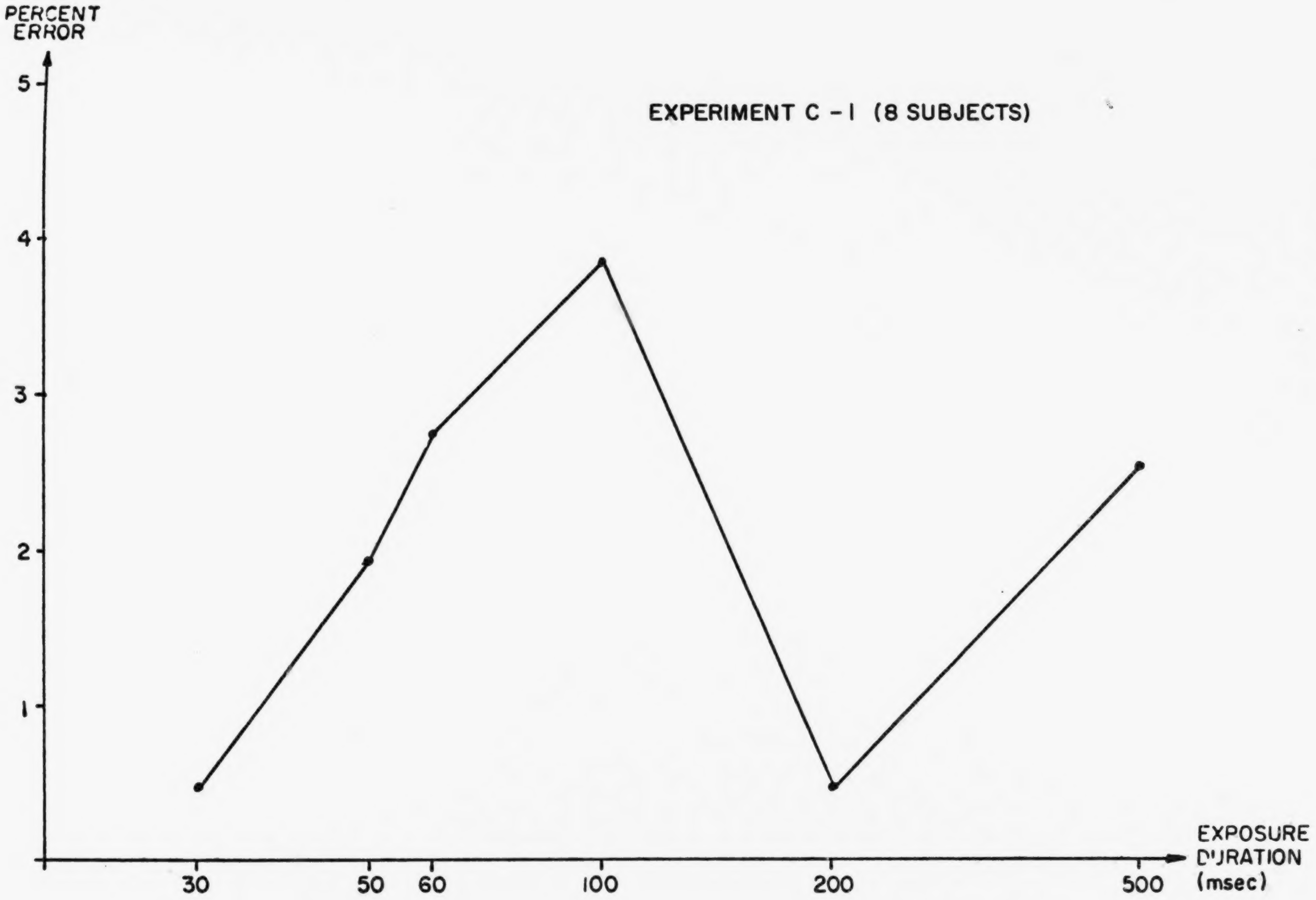

Figure C.3. Percent Error vs Duration--Vertical 1 × 6 Array

in Appendix A if top and bottom are regarded in the same way as left and right. The subjects again apparently "measure" distance from the boundary to deduce the pattern structure.

The high error rate at 500-msec duration is considered coincidental. Of the sixteen errors recorded at this duration, fifteen were made by three of the eight subjects. Furthermore, eight of these fifteen errors were made on the same pattern exposed at the same time to only the same three subjects. In all probability, some exposure artifact such as a defocused or misoriented image was responsible for this error.

C.2. Experiments with a Black-on-White 1 x 6 Array*

Three experiments were conducted with a black-on-white linear 1 x 6 array (horizontally oriented) to provide additional data on the unusual error performance measured with the white-on-black array. In the first a revised version of the array used in the experiment described in Appendix A was employed. This array had black squares on a white surround. The changes in light level from dark preexposure field to bright exposure back to dark postexposure field would be expected to cause pronounced negative afterimages for short duration exposures.

Nine subjects were exposed to six test runs (one each at durations of 30, 50, 60, 100, 200, and 500 msec) which consisted of thirteen different patterns of black and white squares. The only difference between this experiment and those described in Appendix A and in section C.1 was that the subjects were instructed to mark X's in the positions of the black squares for each exposure.

The over-all percentage of error was 0.96 percent, a factor of 2.5 lower than for the comparable experiment in Appendix A. Figure C.4 demonstrates that the percent error versus duration curve again exhibits a peak between 50 and 60 msec. Figure C.5 shows the distribution of errors with respect to position for Experiment C-2. As expected, this curve indicates an almost identical distribution of errors for the black-on-white and white-on-black matrices. The similarity in shape of the error-versus-duration curves for the two matrices, with the lower error rate observed for the black-on-white matrix, may be attributed to two factors:

1. The mechanism that causes the peaking is the same for both cases, but the greater "visibility," or clarity, of the black-on-white matrix improves performance.
2. The unstable negative afterimage created by the 50-to-60-msec duration exposures is not responsible for the peaking because the situation, which presumably results in the more pronounced afterimage, is characterized by improved performance.

**The author gratefully acknowledges the assistance of Mr. R. Spann in performing the experiments described in this section.*

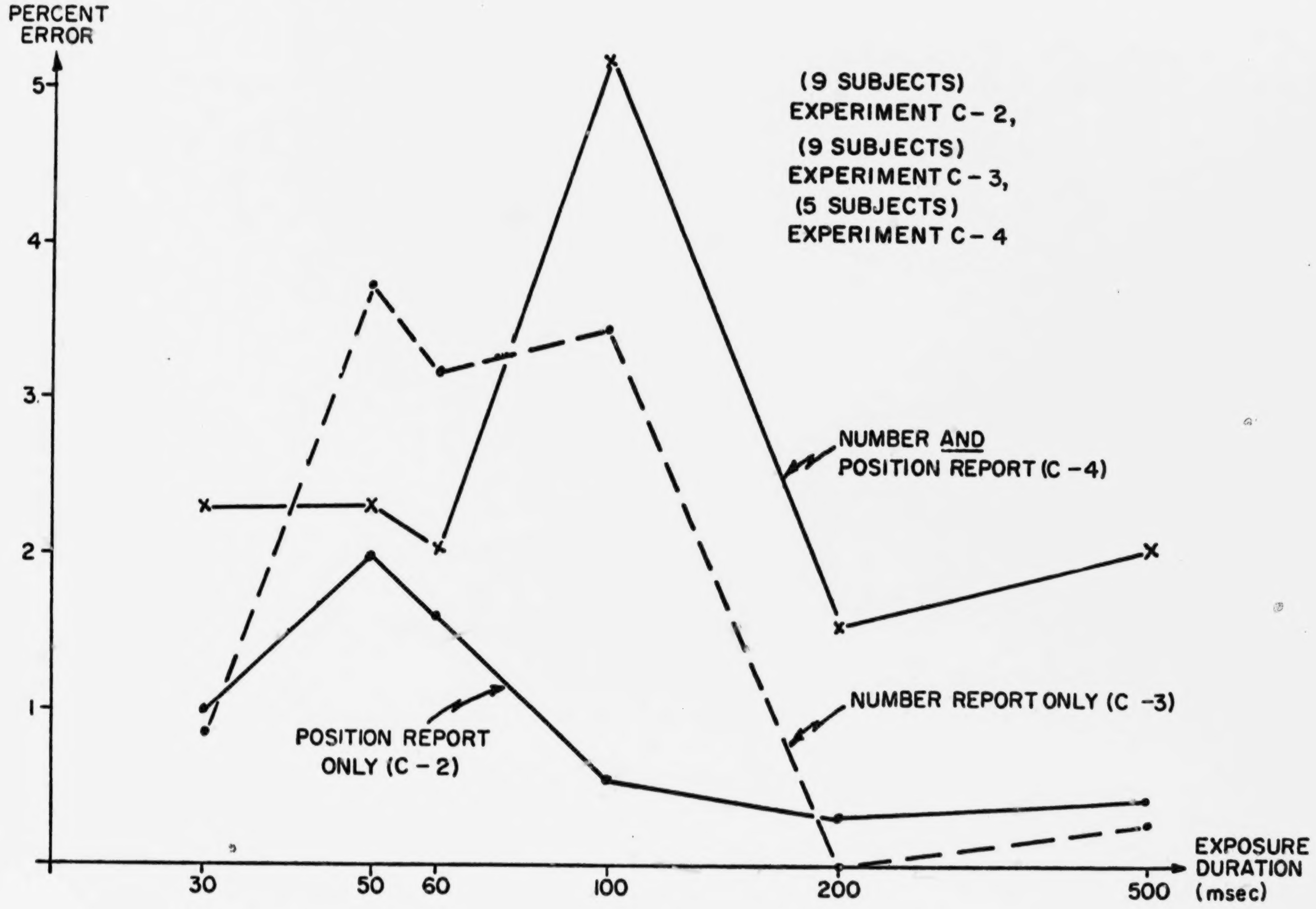

Figure C.4. Black-on-White 1 × 6 Array--Square and Numeral Reports

To evaluate these alternatives, two experiments were conducted.

The display shown in Figure C.6, which consists of an identical 1 x 6 matrix with three numerals in various combinations of the six entries, was exposed exactly as in Experiment C-2. Subjects were shown the sequence of exposures twice; on the first run (Experiment C-3) they were required to record only the numerals (in any order) on a three-block answer blank. On the second run (Experiment C-4), they were asked to record the numerals in their correct positions in the display. Numerals used did not form any regular sequence (like 123), nor was the same numeral used twice in the same display.* The error-versus-duration curves for these cases are shown in Figure C.4. The over-all error for the numeral report case was about 2 percent; for the numeral plus position report case, the over-all error was 2.55 percent. It should be noted that only three possible errors per exposure were considered in computing the error curves for the numeral report case. The shapes of the error-versus-duration curves indicate peak errors for numeral report over the range from 50 to 100 msec, whereas the error for numeral plus position report peaks only at 100-msec durations. Thus, from these experiments, we cannot draw any positive conclusions about the phenomenon that causes this peak. However, a few statements are in order. Because the peaking time changes for the three experiments, peaking is not caused by any system response to special light-versus-time effects such as the Broca-Sulzer phenomenon and the like. The peaking most probably is caused by the mechanics employed by the subjects when they are confronted with having to perform the three different tasks. The difference between the postexposure eye motions measured for exposures to the subject matter in Experiments C-2 and C-4 (see section 5.2) suggests that whatever phenomenon is responsible for this behavior, it is related to voluntary eye motion. Furthermore, the difference in error position for the two cases (see Fig. C.5) indicates that the subject has trouble with the far right entry more often when making a numeral plus position report.

REFERENCE

1. E. Averbach and G. Sperling. "Short-Term Storage of Information in Vision," *Proceedings--Fourth London Symposium on Information Theory*. London: Butterworth, 1961, pp. 196-211.

**Subjects were given this information.*

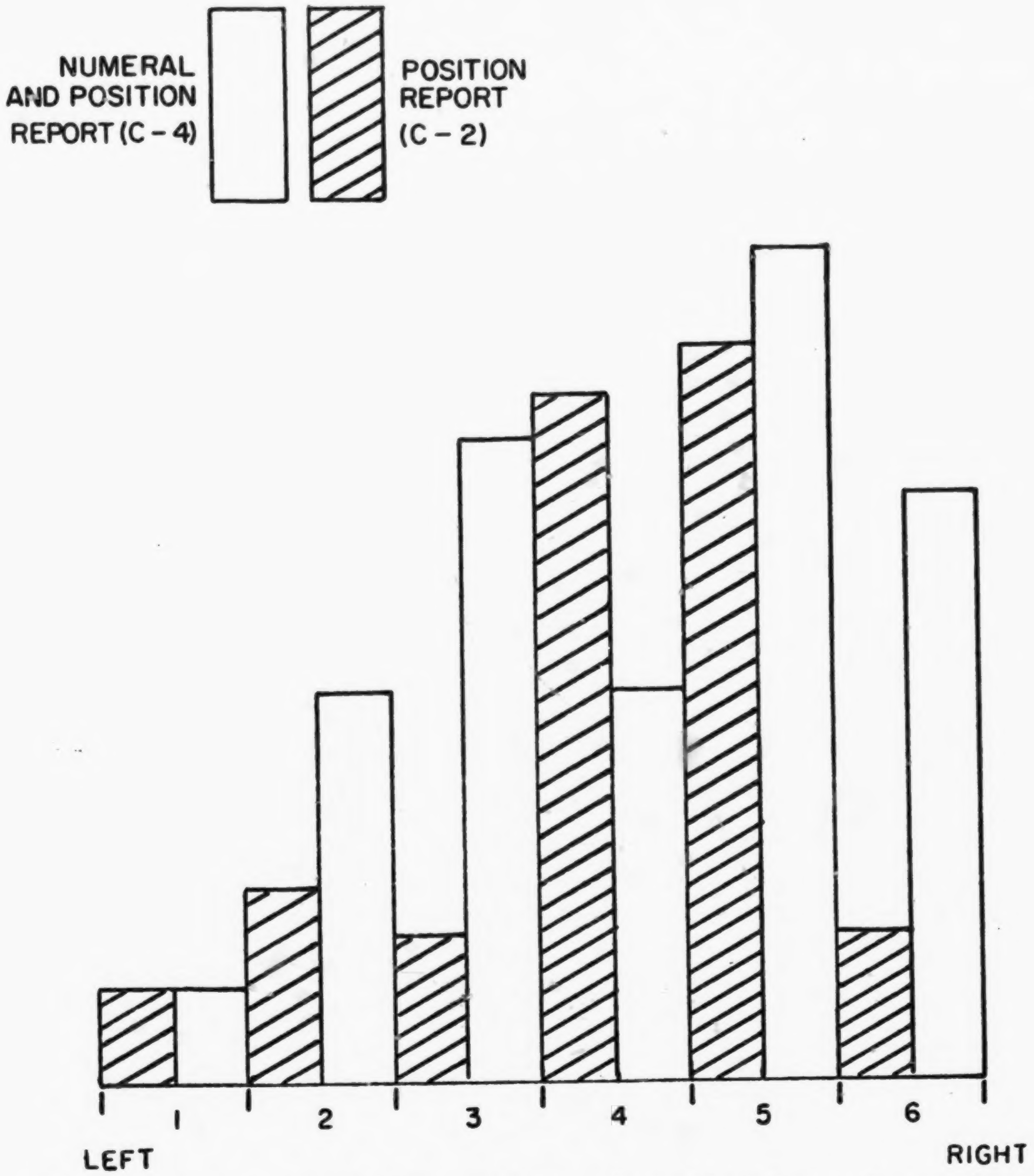

Figure C.5. Position Error Distribution--Experiments C-2 and C-4

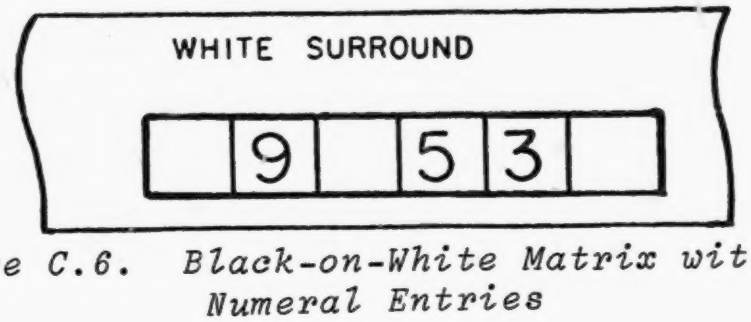
WHITE SURROUND
9
5
3

Figure C.6. Black-on-White Matrix with Numeral Entries

Appendix D

INFORMATIONAL ASPECTS

Since 1949, the year of Shannon's work on the quantitative measurement and manipulation of information (1), psychologists have tried to use statistical measures of information to define information transmission by the human through his various sensory modalities. Entire symposia have been devoted to the marriage of psychology and information theory (2). The conceptual and analytic advantages offered by regarding the human as an information channel characterized by a channel capacity have probably been responsible for this work.

Several attempts have been made to measure the channel capacity of the human visual system* with respect to various inputs. For instance, in reading English text (if one begins from Shannon's figure of 1.5 bits per letter information content), the actual amount of information absorbed or perceived is measured in tens of bits/sec (3). Quastler (on the basis of several experiments involving various sensory modalities) estimates that the highest sustained sensory information rates are about 25 bits/sec. This is vastly lower than the 4.3×10^6 bits/sec derived by Jacobsen through consideration of the retinal mosaic and visual acuity alone (4).

The experiments of Miller, Brunner, and Postman (5) using lists of eight letters each, whose information content is derived from the zerogram, monogram, and so on, redundancies of ordinary English indicate information processing at a constant rate for this source of approximately 10 bits/sec.

It is much more difficult to describe quantitatively the information content of visual patterns from an arbitrary source--even from the finite ensemble described in section 2.2. Subject to certain assumptions, we can, however, use the notion of statistical information measure to derive an upper bound to information content.

Consider an $M \times N$ matrix of elements (squares) which are filled to form a pattern. Assume that $n (n \leq MN)$ elements are filled. The number of possible ways A in which we may select the n filled boxes (number of possible patterns) is given by Equation (D.1).

$$A = \frac{(MN)!}{n!(MN - n)!} \tag{D.1}$$

**It should be noted that when psychophysical measurements are used, the capacity of the combination of the visual channel and response channel is usually measured. Furthermore, most measurements of this type are merely intended to measure information transmission for a given input set rather than channel capacity as it is formally defined.*

The maximum entropy $H_{\max}(n)$ of this set occurs when the probability distribution is uniform over all the patterns, or when $P(A_i)$, the probability of the i^{th} combination, is given by Equation (D.2).

$$P(A_i) = \frac{n!(MN - n)!}{(MN)!} \tag{D.2}$$

Under these circumstances the average maximum entropy is

$$H_{\max}(n) = - \underset{i}{\quad\quad} P(A_i) \log_2 \frac{1}{P(A_i)} = \log_2 P(A_i) \tag{D.3}$$

or

$$H_{\max}(n) = \log_2 \frac{(MN)!}{(MN - n)!\ n!} \tag{D.4}$$

Figure D.1 shows the dependence of $H_{\max}(n)$ on n for $MN = 108$ (a 9 x 12 matrix).

The results in Figure D.1 must be carefully interpreted. Bit figures refer to the number of bits that must be sent, given that n elements are filled in, if (essentially) the coordinates of each point are transmitted. Clearly, this is not the way that the human generally transmits information about patterns. The encoding used by the human effectively takes into account the information shared by the pattern elements. For this reason these bit rates are upper bounds on the information per exposure.

By varying the "grain size" to number of grains in the pattern (n/MN), various maximum information rate sources can be constructed from matrix patterns (6). Clearly, the information content of any pattern defined in this way may be changed by varying the size of the ensemble, without changing the pattern at all. This is one difficulty encountered in applying statistical information measures in bit notation to psychophysical stimuli.

A quantitative measure of stimulus "information" that does not suffer from some of the psychophysical defects of the common statistical measures (bits) is provided by the concept of coordinality (7). This concept supplies a means of predicting information-transmission performance in terms of the number of dimensions or coordinates of the source. It is, to a certain extent, predicated upon the notion that humans are capable of making many more separate "measurements" of a stimulus when the measurements are grossly quantized in several dimensions than when the measurements involve fine quantizations along a single dimension (8). The concept is quantified by Klemmer (7) to the point where a general theorem may be stated:

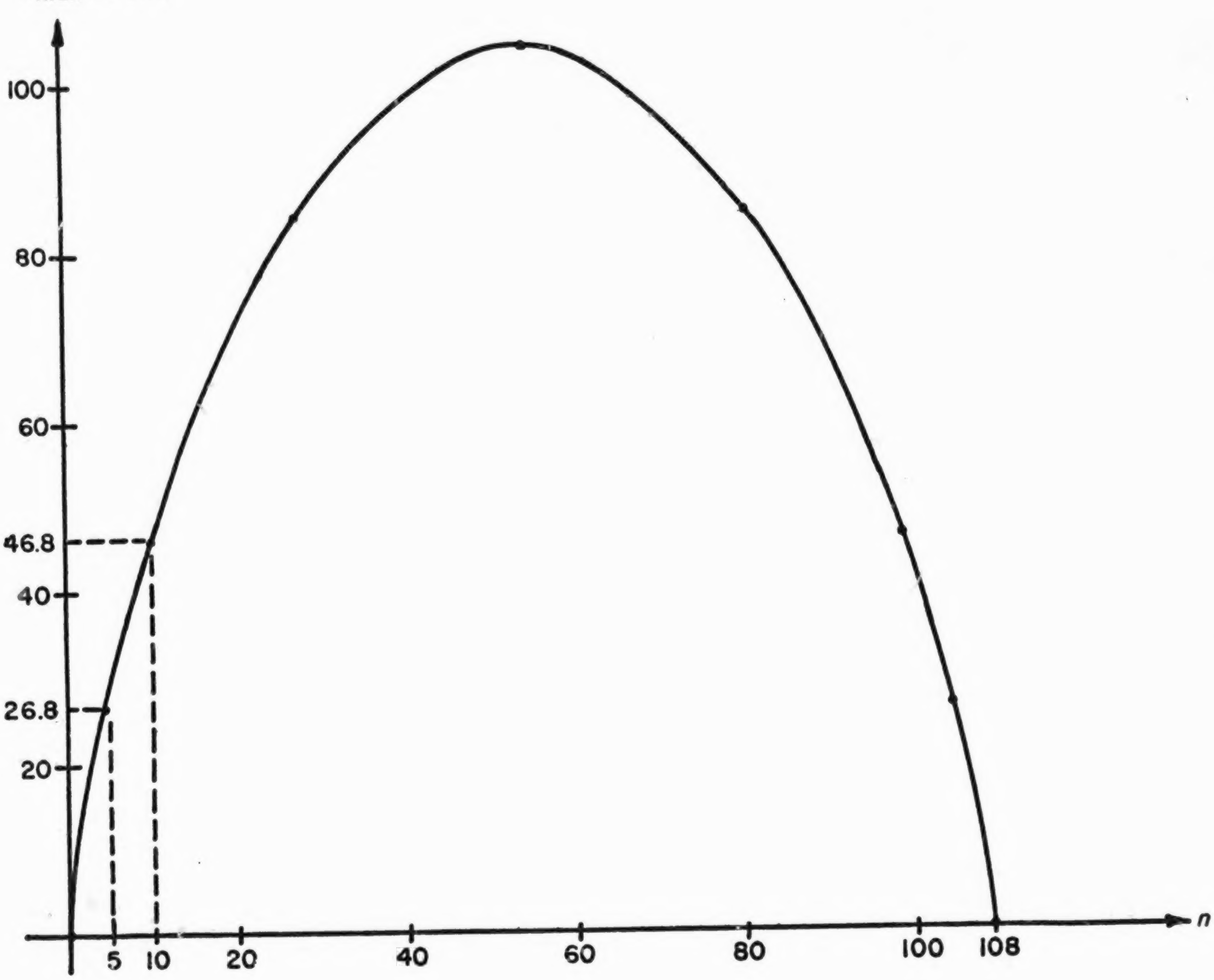

Figure D.1. $H_{max}(n)$ *vs* n

The information transmitted in bits from a visual display is proportional to the logarithm of the number of coordinates necessary to describe stimulus display.*

**Author's statement.*

In the following paragraphs the coordinality concept is shown to agree (approximately) with the general results of the pattern-recognition experiment. Of course, the usefulness of this concept is dependent upon our ability to determine the coordinates of the stimulus.

The maximum source information rate $H_{\max}(n)$ for patterns formed by filling in n elements of a 108-element matrix (9 x 12) has been computed. For the (5)- and (10)-patterns, $H_{\max}(n)$ becomes

$$H_{\max}(5) = 26.8 \text{ bits} \tag{D.5}$$

$$H_{\max}(10) = 46.8 \text{ bits} \tag{D.6}$$

Thus, on the average, (5)-patterns contain about 5.4 bits per element and (10)-patterns contain about 4.7 bits per element. Because it is clear that some patterns are much "easier" to recognize or reproduce than others, we are lead to believe that the information content of the easier patterns is smaller than that of the more difficult patterns. In general, this reduction in information content occurs because the elements share information among themselves. The extent to which this information is shared is often called the redundancy of the pattern. The actual information content i of any particular pattern from the (5)- or (10)-set is reduced by the total amount of information shared between the pattern elements.

In this research organizational principles have been stressed rather than information transmission from pattern ensembles or information sharing between pattern elements. An attempt has been made to divide typical patterns into equivalence classes on the basis of performance in pattern-reproduction experiments for short-duration exposures. The accuracy of the measurement techniques now available does not warrant fine distinctions between individual patterns in the ensemble. On the other hand, certain invariant features of the results of pattern-reproduction experiments which make gross classification feasible have been considered.

In fact, the simple division of (5)- and (10)-patterns into random and structured groups provides a basis for performance prediction in several different experiments. The techniques for making such a distinction between patterns and the utility of this distinction were discussed in section 3.

D.1. Information Transmission from Pattern Sources

At this time the results of Experiment 2 will be related to statistical information measures because:

1. The literature contains few realistic information-transmission rates or rate bounds for pattern sources.

2. Several organizational principles demonstrated in the literature with much smaller input ensembles may be illustrated for pattern ensembles.

3. The technique of best-fit grading (which adds to the subject's response) has some interesting informational aspects.

To summarize the results of Experiment 2 in a manner convenient for an information-theoretic analysis, four sets of experimental data have been averaged, at each exposure duration, over all subjects: the best-fit grade for (10)-patterns, the best-fit grade for (5)-patterns, the absolute registration grade for (5)-patterns, and the absolute registration grade for (10)-patterns. These average values are shown in Figure 3.10. For ease of interpretation the author has approximated the functional relations in Figure 3.10 with straight lines.

It would be very convenient to state that averaging performance grades over the ten (10)-patterns and ten (5)-patterns yields an average measure of performance over the ensemble of all (5)- and (10)-patterns. But there is no real basis for the premise that performance with the patterns used constitutes an appropriate statistical sample of performance over the entire ensemble. Thus all informational inferences are for the simple ten-pattern ensembles and should be regarded as such.

The experimental data in Figure 3.10 are related with four straight lines as indicated. In general, the subjects are able to register correctly about twice as many elements from the (10)-patterns as from the (5)-patterns (lower two lines in Fig. 3.10). The best-fit grades are also much better for the (10)-pattern set, and the slopes of the four curves differ slightly.

If each of the n elements of the matrix patterns is independent (in the sense that the minimum amount of information is shared between elements), the entropy per element (or square) is bounded by Equations (D.7) and (D.8).

$$H_5 \text{ (square)} \leq 5.4 \text{ bits/element} \tag{D.7}$$

$$H_{10} \text{ (square)} \leq 4.7 \text{ bits/element} \tag{D.8}$$

Furthermore, the information required on the average to locate the coordinates of a single element in 108 is $H_0 = 6.75$ bits. The average "distance" between the absolute registration and best-fit curves in Figure 3.10 is

$$D_{10} = 2.0 \text{ squares} \tag{D.9}$$

$$D_5 = 1.7 \text{ squares} \tag{D.10}$$

for the (10)- and (5)-patterns, respectively. If each element correctly marked conveys as much information as any other element, we are on the average effectively adding the amount of information implied by correct registration of a single element by best-fit grading. Call this additional information $H_r(n)$. The difference in bits for the absolute registration curves and the best-fit curve for each set should be

$$H_r(n) = D_n H_n \text{ (square)} \qquad \text{(D.11)}$$

or

$$H_r(5) = D_5 H_5 \text{ (square)} = 1.7(5.4) = 9.2 \text{ bits} \qquad \text{(D.12)}$$

$$H_r(10) = D_{10} H_{10} \text{ (square)} = 2.0(4.7) = 9.4 \text{ bits} \qquad \text{(D.13)}$$

Thus, the information added by best-fit grading is the same for the (5)-patterns and (10)-patterns and is larger than $H_0 = 6.75$ bits predicted from the simple assumption that such grading merely supplies, on the average, the coordinates of a single element of the pattern to each subject's response.

The best-fit data in Figure 3.10, which approximate a straight line, imply that the information actually conveyed (H) in an exposure duration T from the pattern ensemble is given by

$$H \approx K(n) \log_{10} T + C(n) \qquad \text{(D.14)}$$

where $K(n)$ is the slope of the absolute registration curves in Figure 3.10 modified by the H_5 (square) and H_{10} (square) bit weighting.

$$K_{(5)} \quad 0.6(5.4) = 3.24 \text{ bits} \qquad \text{(D.15)}$$

$$K_{(10)} \quad 1.1(4.7) = 5.17 \text{ bits} \qquad \text{(D.16)}$$

Thus, the average performance curves can be interpreted to yield an upper bound on human information transmission from this source over the one-glance region for which they have been measured. Furthermore, they indicate that performance improves approximately as the logarithm of the exposure duration with greater improvement (increase in bits transmitted per unit time difference) noted for the (10)-patterns.

Figure D.2 indicates the upper bound on transmitted information as a function of exposure duration for the measured absolute registration grade for both the (5)- and (10)-patterns. These curves indicate peak average information transmission rates (at one-frame exposure) below 135 bits/sec for (10)-patterns and 70 bits/sec for (5)-patterns. The maximum average information rates over the 3-sec (50 frame) range of the one-glance region are measured at less than 5.5 bits/sec for (10)-patterns and 3.1 bits/sec for (5)-patterns. The long duration rates clearly reflect saturation of the span of immediate memory for total report (8, 9).

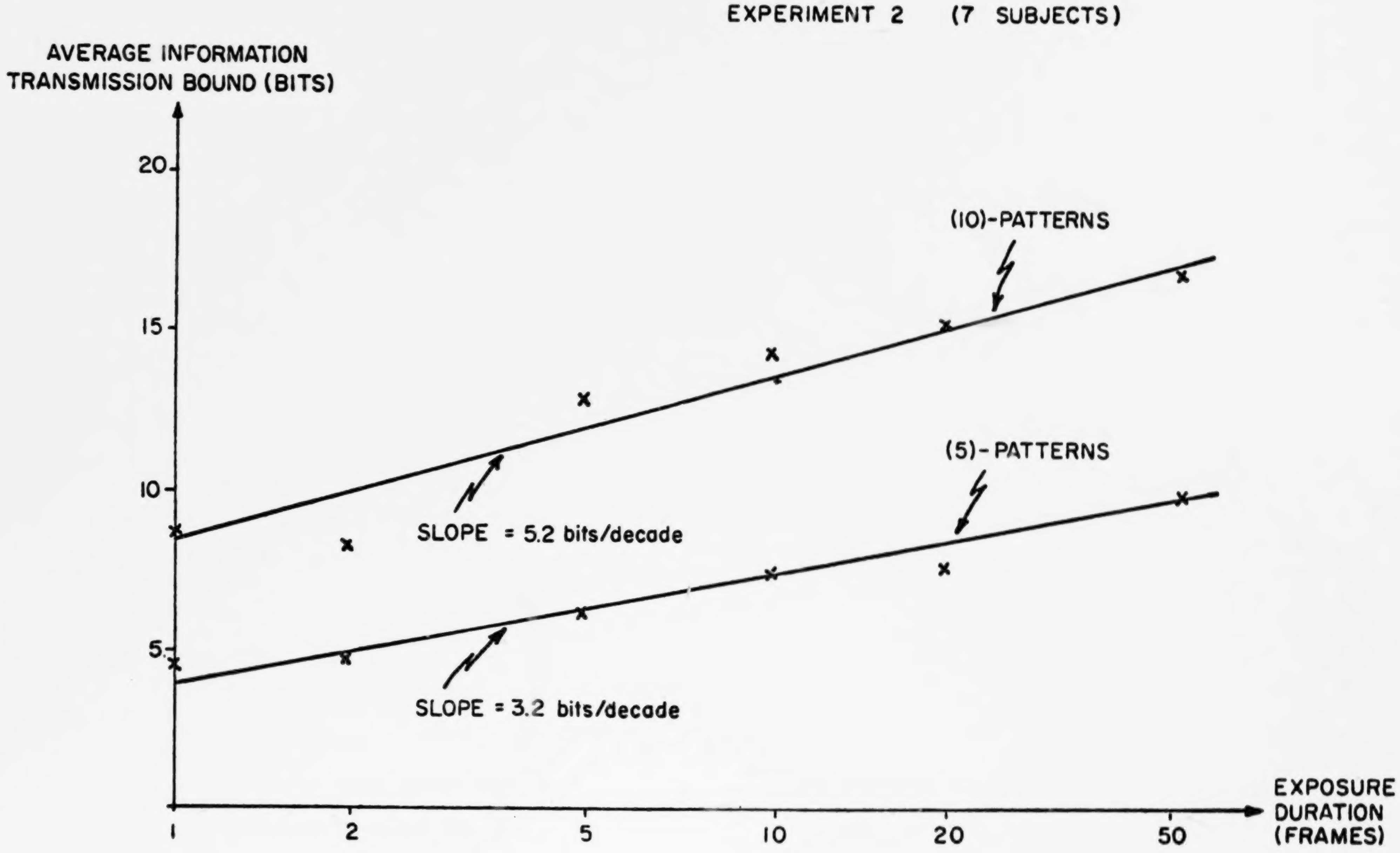

Figure D.2. Information Transmission Bounds vs Duration for Absolute Registration

The high upper bounds on the short-duration rates (135 and 70 bits/sec) are more difficult to explain. Averbach and Sperling (10) suggest that rates for short-duration exposures are "likely to be widely erroneous" when the rate computation is based upon exposure duration because the stimulus persists in some form of short-term memory for much longer periods. Often, this persisting visual image is the common afterimage associated with tachistoscope presentations. For the motion picture presentations used here, there is no apparent afterimage, but other forms of short-term storage (discussed in Chapter 4) may account for image persistence.

The information rates $K(n)$ are seen to vary (approximately) as the logarithm of the number of elements in the display (4, 5), at least for $n = 5$ and $n = 10$;

$$\frac{K(10)}{K(5)} = 5.17 = 1.59 \qquad (D.17)$$

and

$$\frac{\log\ (10)}{\log\ (5)} = \frac{1.00}{0.69} = 1.45 \qquad (D.18)$$

These rates are indicative of the effects of dimension of the ensemble as well. The difference between $K(10)$ and $K(5)$, if one assumes that going from five to ten elements doubles the effective dimension of the ensemble, should be 1.7 bits (11).

$$K(10) - K(5) = 1.93 \text{ bits} \qquad (D.19)$$

This agreement is significant in establishing the validity of simple dimension measures in the approximate prediction of information transmission from large ensembles. The small differences noted here may be due to the fact that the ten pattern averages for the (5)- and (10)-patterns are not representative of the complete ensemble.

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THE VESTIBULAR SYSTEM AND HUMAN DYNAMIC ORIENTATION*

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Massachusetts Institute of Technology

1. INTRODUCTION

Daily human activity includes complex orientation, postural control and movement coordination. All these tasks depend upon his perception of motion. The vestibular system is recognized as the prime motion sensing center in the human. Its sensing capabilities are probably most compatible with every-day movements of man relative to his surroundings. However, man-made vehicles have extended the operating environment of man, and thereby delegated new responsibilities to human's sensory system.

This thesis studies primarily the vestibular sensory system. Augmented by tactile and visual information, the perception of motion by the vestibular sensors is used in man's orientation in three-dimensional space. In a manual control system, all these sensors provide input information for the motion control commands of the operator.

Feedback control theory and its methodology are used to describe the characteristics of the sensors in conjunction with vehicle control. Mathematical models are presented for the dynamic response of the vestibular sensors. Analogies between these sensors and electromechanical instruments designed for similar functions are drawn. The control activities of the human operator in representative manual control systems with and without motion inputs are studies. The characteristics are summarized by a new nonlinear model as well as the conventional describing functions. The resultant control models will be of value to control engineers concerned with the performance of manual control loops. The models for the vestibular sensors demonstrate functional relationships which can lead to further physiological research. Both engineers and physiologists will gain insight into the capabilities of an important biological system, and its use by the human in tasks of orientation control.

Scope of the Research

Control of orientation depends upon the ability to determine, quantitatively, changes of orientation with respect to a given kinematically defined reference orientation. As in navigation and control, orientation is defined as the attitude and position of a body-fixed coordinate system, measured relative to a given earth-fixed frame.

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* *This article is derived from Dr. Meiry's doctoral dissertation which was submitted to the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, in June, 1964.*

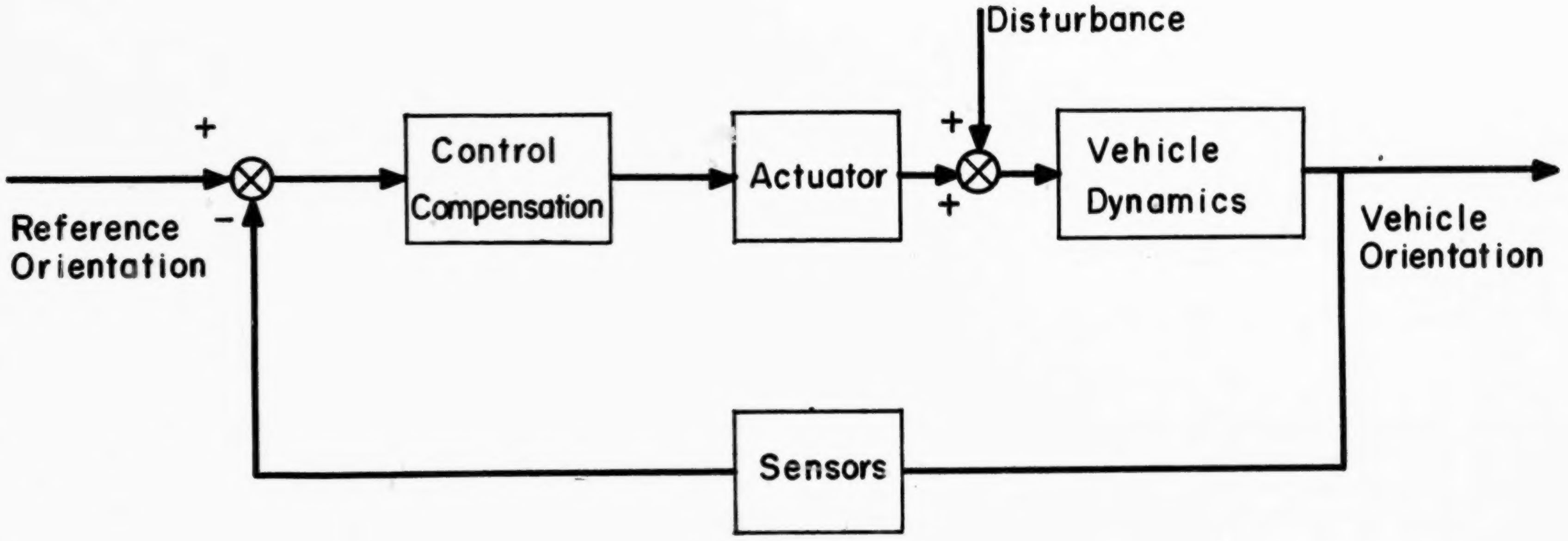
The feedback loop for any orientation control, automatic or manual, can be represented by the functional block diagram in Figure 1.1a. For an electromechanical servo system, the functional blocks are identifiable, their input-output relations are measurable, and the whole system is amenable to rigorous mathematical evaluation. When the task of orientation control is given to a human operator, the system block diagram is modified to that of Figure 1.1b. Application of servoanalysis to such manual control systems has two major goals: *(1)* mathematical models of each of the "components" (sensors, compensation, etc.) may be identified; *(2)* overall human operator transfer functions may be obtained and applied to manual control system analysis.

In general, orientation control by a human operator is a multi-input control system as shown in Figure 1.2 (153). Human control characteristics in fixed base simulation, with visual input and manual output, have been studied extensively for a wide variety of controlled elements (50, 89, 129, 148). The research in this thesis is concerned with another important path undertaken through this loop. Sensory information is processed through the mechanism of the vestibular system, supplemented by tactile sensation and visual reference. At the motor end, the operator uses manual control. The central nervous system (CNS) is the controller for the control system. Time variant characteristics of the operator, such as adaptation and learning are not included in this study. This subsystem of the general orientation control problem is given in Figure 1.3.

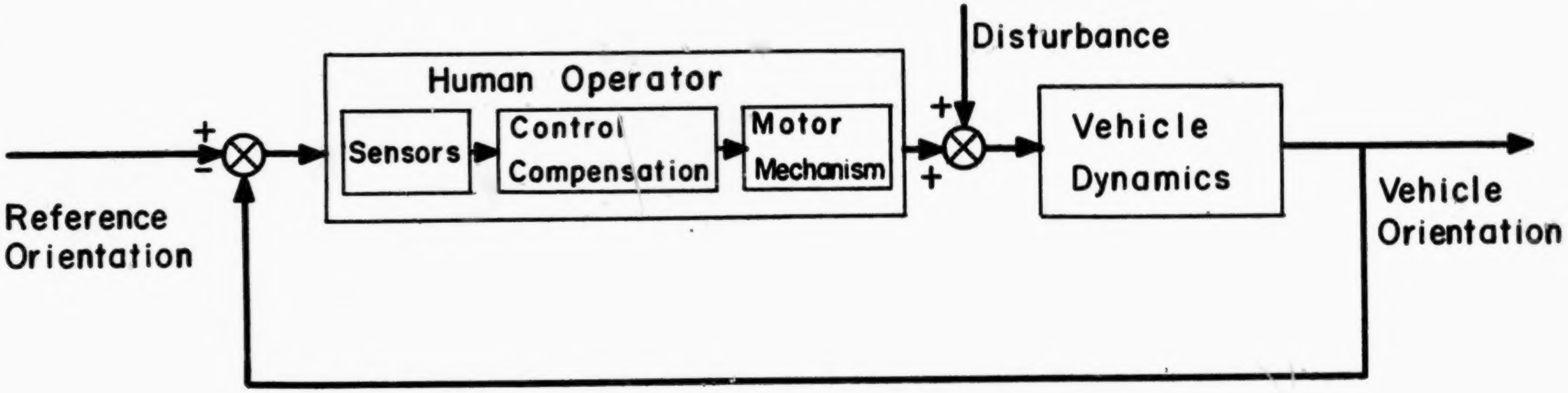
The pattern of research follows the techniques that would be used in analysis of a comparable automatic control system. The dynamic characteristics of the vestibular system are studied for their inherent interest and also as a "component" of the operator. Compensating eye movements in the presence of head and body motions are discussed from a space stabilization point of view. The capabilities of the human operator are reviewed on the basis of the information he receives from his various sensors. Manual control of orientation, when the vehicle is driven in modes of motion specific to a given sensor or combination of sensors, is analyzed in terms of operator describing functions. Finally, the compensation capabilities of the human operator in controlling the orientation of an unstable system are investigated in pure visual, pure vestibular, and combined modes. Results are presented in terms of an on-off model for the operator and analyzed in the phase plane.

Application of the Research

Physiology and Biology. Subjective orientation is a result of the processing of numerous inputs coming from separate sensors. In physiology, motion is sensed by receptors informing


Disturbance
+
Control
Compensation
Actuator
+
+
Vehicle
Dynamics
Reference
Orientation
-
Vehicle
Orientation
Sensors

a. General Control of Vehicle Orientation


Disturbance
Human Operator
+
Sensors
Control
Compensation
Motor
Mechanism
+
+
-
Vehicle
Dynamics
Reference
Orientation
Vehicle
Orientation

b. Human Operator Control of Vehicle Orientation

Figure 1.1. Block Diagram for Control of Vehicle Orientation

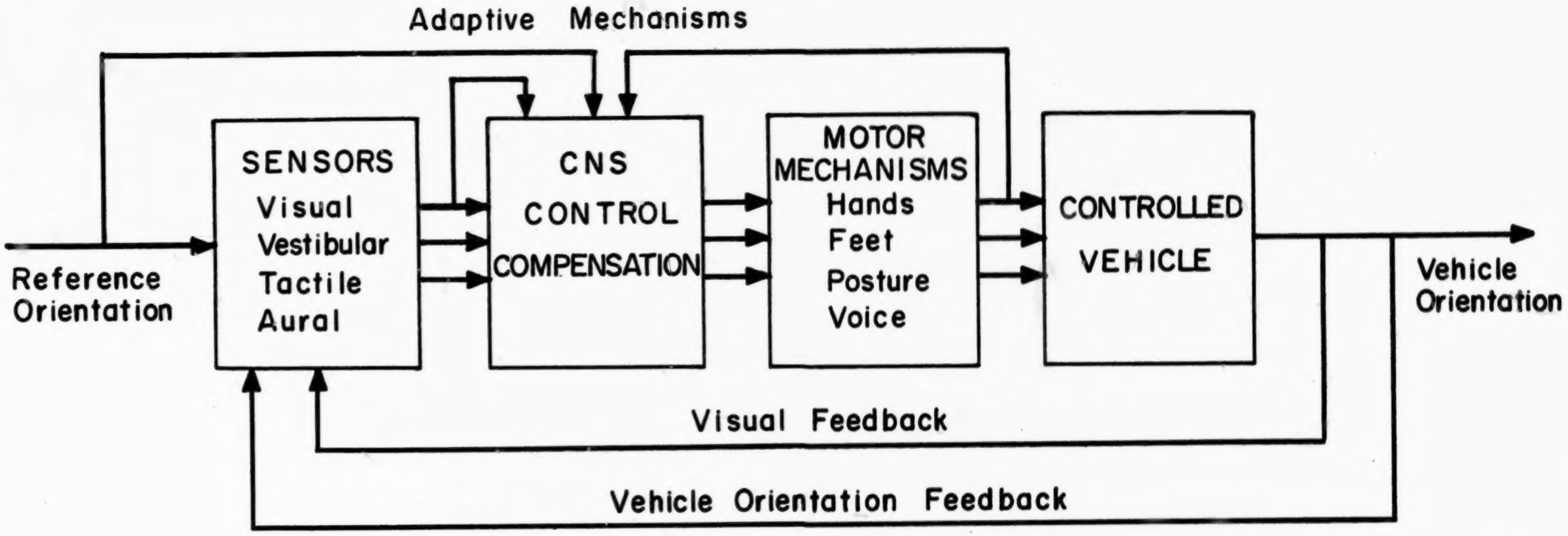

Adaptive Mechanisms
SENSORS
Visual
Vestibular
Tactile
Aural
CNS
CONTROL
COMPENSATION
MOTOR
MECHANISMS
Hands
Feet
Posture
Voice
CONTROLLED
VEHICLE
Reference
Orientation
Vehicle
Orientation
Visual Feedback
Vehicle Orientation Feedback

Figure 1.2. General Block Diagram of the Man-Vehicle Control Problem (Ref. 153)

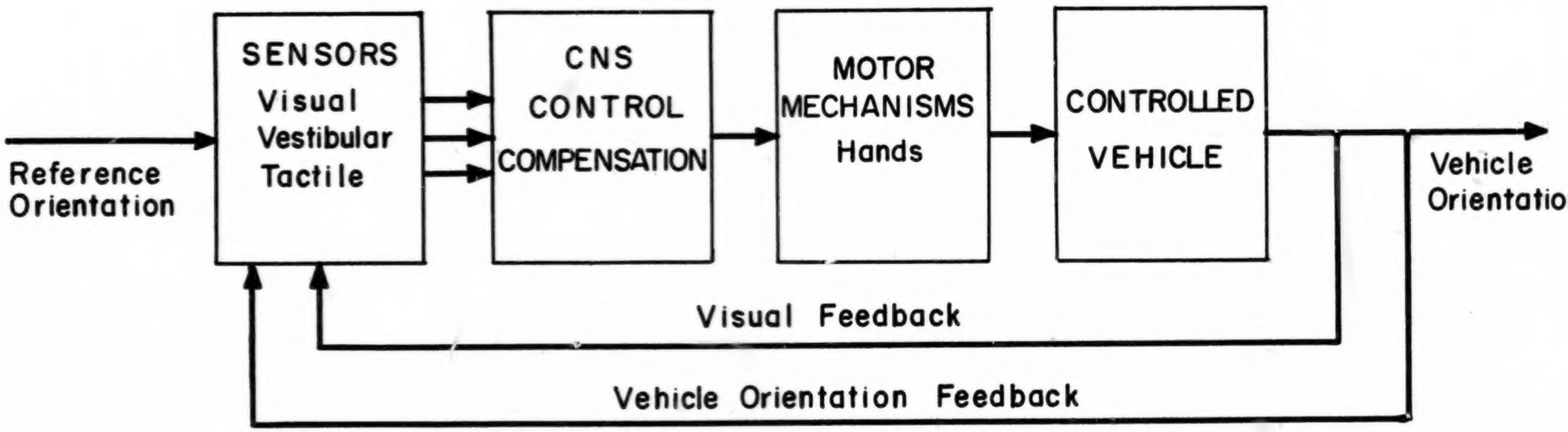

SENSORS
Visual
Vestibular
Tactile
CNS
CONTROL
COMPENSATION
MOTOR
MECHANISMS
Hands
CONTROLLED
VEHICLE
Reference
Orientation
Vehicle
Orientation
Visual Feedback
Vehicle Orientation Feedback

Figure 1.3. The Man-Vehicle Control System Studied in This Thesis

the brain about localized sensations; in feedback theory this is considered as a system with multiple sensors feeding a controller. The goal of the research in the two fields are complementary. The control engineer is interested in the overall performance of the sensors, the physiologist in the description of the associated body mechanisms. Engineering characteristics of the vestibular system, the neck proprioceptors or the body pressure receptors described in terms of a model, do not guarantee a physiological correspondence. The mathematical model describes the sensors' response in a compact mathematical notation and is easy to simulate and analyze. There is no reason to expect that a lag-lead network corresponds to the actual biological mechanism. However, the underlying physiological processes associated with a model could be investigated. The physiologist, guided by the functional relationship of the mathematical model, could postulate and search for the physiological counterparts of the engineering analog.

Aerospace Medicine and Psychology. Is the human fit to accomplish space missions? Is a given individual conditioned to the expected motion parameters of the mission? These questions are of great importance in this era of rapid technological achievements. The common denominator of this medical and psychological interest and responsibility is the ability of the human to judge his spatial orientation.

Spatial disorientation or vertigo may be crucial for survival and successful completion of a mission. Poor motor coordination and prolonged reaction time are manifestations of inability to deal effectively with the environment. The psychological symptoms accompanying vertigo are equally serious.

The mathematical model of the vestibular system is basic for evaluating the expected subjective orientation of the human. Expected vehicle motions from a mission profile may be applied to the vestibular system model to predict potential difficulties. On the basis of the vestibular model, a medical criterion for personnel selection may be developed along with a minimum standard for medical fitness of flying personnel.

The psychological training of the human should not be underestimated. Pilots have been trained to fly by instruments and to ignore conscious sensations of body orientation. Ice skaters and ballet dancers learn to suppress certain vestibular or visual information. Appropriate psychological conditioning must consider the environment where the human will be functioning. This environment imposes dynamic conditions which the operator compares to a set of previous experiences. The observations or illusions which arise under these conditions are a function of his previous exposure to similar input accelerations. The mathematical model of the vestibular system is valid for the normal environmental conditions for man on earth. Training for operation in different environments should be considered as modifications with respect to this built-in "reference."

Control Engineering and Human Engineering. The control engineer attempts to associate a mathematical description with each physical element of a control system. This description represents a relation between the input variable to the component and its output regardless of the type of physical parameters involved (acceleration, current, torque, etc.). A body of test methods has been developed for identification of these input-output transfer functions. Similarly, methods of analysis are available to evaluate the stability and performance of a control system on the basis of the characteristics of its individual components. In a preliminary design of an automatic control system, the control engineer can analyze a whole series of systems, select components with characteristics meeting his criteria and make design decisions on the basis of mathematical analysis.

The human has sensors, can act as a controller and can compensate, and has the strength to execute control decisions. Each or all of these human capabilities can be utilized in a control system. However, the analysis of manual control systems, even in the preliminary design stage, is still generally done by simulation. This approach is necessary, since our current knowledge of the engineering characteristics of man is quite limited. Simulation is certainly a necessity in the final design stages of manned systems. However, a degree of flexibility in design of manned systems comparable to that found in automatic system design may be achieved with the formulation of models which adequately represent control characteristics of the human.

The experimental data presented in this thesis is summarized in simple mathematical models of the vestibular motion sensors, a model of the eye control system in the presence of rotational motion, and describing functions for the human operator in manual control systems with motion inputs.

This research work represents a further step in the description of overall human control characteristics and those of his sensors. As such, it can be used to estimate the ability of the human to obtain orientation information with his various sensors and subsequently to utilize it for vehicle orientation control.

Human engineering is concerned with the accommodation of the human operator in an environment which will allow him to perform his task most efficiently. Relevant parts of this research concern the effects of head motion on the human's ability to fixate an instrument or to perceive vehicle motion. The models of the vestibular sensors and the eye movement control system can be used as guides for vehicle interior design, appropriate to the control tasks assigned to the human operator.

2. THE VESTIBULAR SYSTEM

The nonauditory section of the human inner ear is the recognized center of motion sensors. This center, the vestibular system, is one of the sensory systems which provide information of body orientation and balance. Because the ability of the human to orient himself and preserve equilibrium with the surrounding environment is a basic prerequisite for normal existence, a sizable research literature is devoted to the various aspects associated with the function of the vestibular system. The medical researchers study the balance mechanisms of mammalians and attempt to correlate their findings with the role and the function of the vestibular system in humans. The dynamic characteristics of the vestibular sensors and pertinent data on thresholds of perceptions of motions with corresponding response times is another field of concentrated research effort.

This section will review the background material on the vestibular system. The next section will analyze the semicircular canals, the human angular accelerometers, with their characteristics as determined by previous work and from experiments by the author. The otoliths, the linear motion sensor of the vestibular system, are the subject of the third section, where experimental results obtained here along with a critical examination of the otolith sensing capabilities are summarized in a mathematical model. These three sections present the physiological and the engineering description of the human motion sensors as known at the present time.

Physiology and Anatomy (7, 76, 77)

The inner ear is divided into two parts: *(1)* the cochlea serving auditory function, and *(2)* a nonauditory portion, the vestibular system. This structure, also called the labyrinth, lodges the sensors associated with maintenance of balance and orientation in three-dimensional space. One distinguishes between the bony labyrinth and the membranous labyrinth. The bony labyrinth is a cavity tunneled in the temporal bone of the skull. Its structure forms three ducts, the semicircular canals, and the vestibule. This elaborate canal system contains in its cavities the membranous labyrinth suspended in perilymph. The suspension system of the membranous labyrinth does not allow it to move relative to the skull. Thus the accelerations acting on the membranous labyrinth are those applied to the head. The bony semicircular canals lodge the three semicircular canals, while the vestibule contains the utricle and the saccule (7). (See Fig. 2.1.) The membranous labyrinth contains fluid called endolymph.

The utricle is the large, oblong sac occupying the vestibule. Its lower part forms a pouch where it thickens over an area of about 6 mm^2 (2 mm × 3 mm), and is known as the macula. The otolith, a gelatinous substance with calcium carbonate

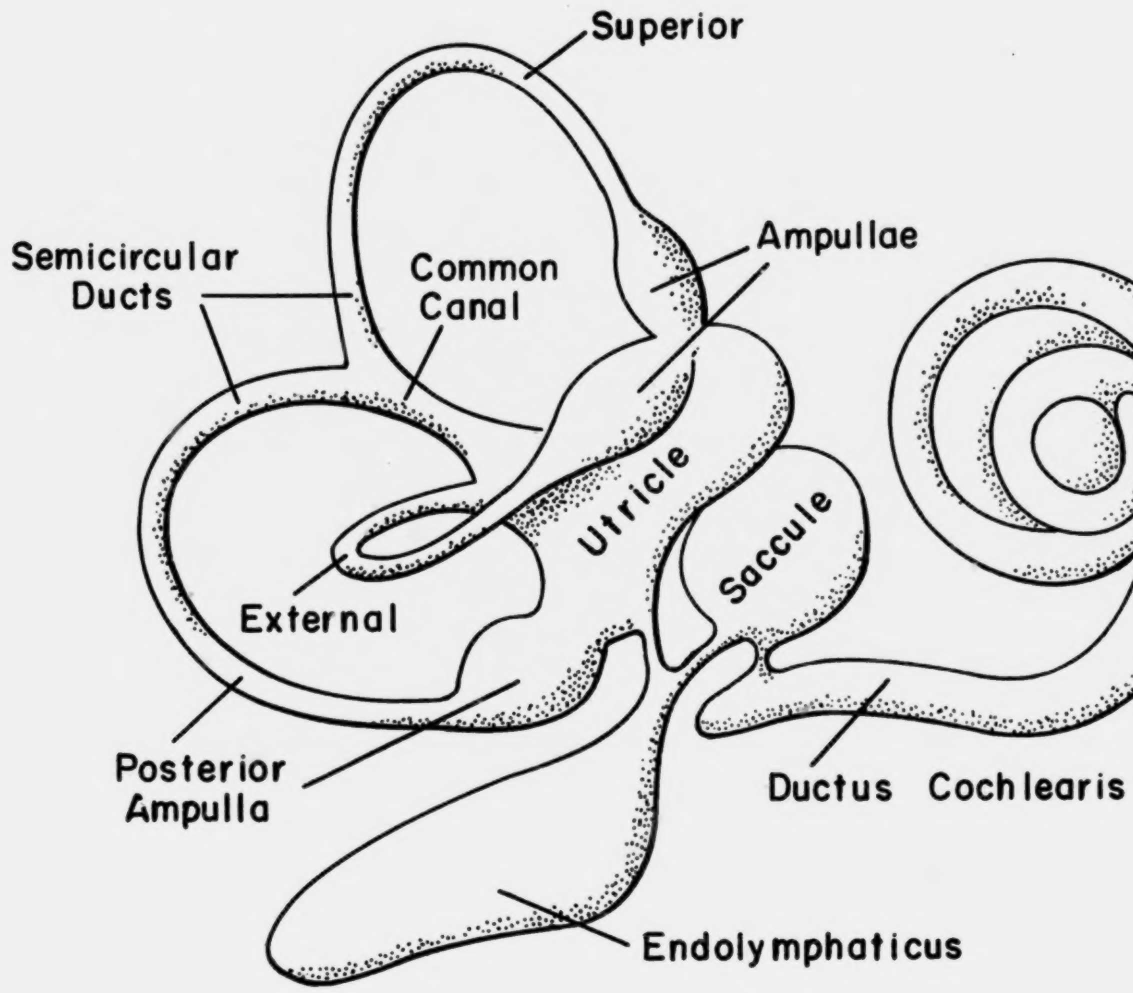

Superior
Semicircular Ducts
Common Canal
Ampullae
Utricle
Saccule
External
Posterior Ampulla
Ductus Cochlearis
Endolymphaticus

Figure 2.1. The Membranous Inner Ear

grains in it, and of specific density of around 2.95, is supported over the macula by strands allowing a limited sliding travel of about 0.1 mm. The macula, the receptor end of this otolithic organ, provides the bed for the utricular branch of the vestibular nerve. It also has sensory hairs imbedded in it, which at their other end penetrate the otolith. Figure 2.2 is a crosssection of the utricle showing the macula and the otolith together with their supporting and sensory cells (77). Note that the macula and otolith are not exactly planar; a small portion of the sensor makes an angle of 120° with the mean plane of the macula. Nevertheless, the plane associated with the utricle is a plane which, for an erect head, is elevated between 26° to 30° above the horizontal plane. The two utricles (one from each inner ear) are located in the same plane.

The utricle is a multidimensional linear accelerometer with the otolith being the moving mass. The plane, associated with the sensor, is relevant in determining the input accelerations to it.

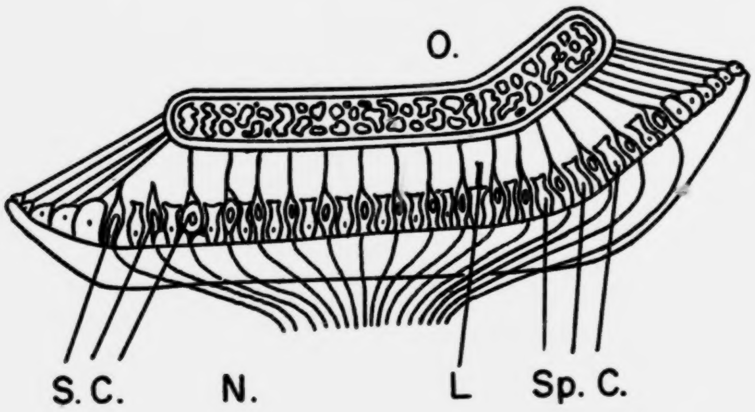


Figure 2.2. Schematic Drawing of a Cross Section of an Otolith and Its Macula

O is the otolith, suspended by strands which run from the margins to the macula, consisting of supporting cells (Sp C) and sensory cells (S C). Between the otolith and the macula there is a thin layer (L) to allow the otolith to slide over the macula. N is the nerve.

The saccule is an organ with histological structure identical to that of the utricle. The plane of the saccular macula is perpendicular to that of the utricle.

The three semicircular canals are above and behind the vestibule. Their structure is planar, lying in planes which are roughly orthogonal to each other. The horizontal (lateral) canal is in a plane elevated about 25° to 30° from the horizontal plane. The other two canals, the posterior and the superior vertical, are in approximately vertical planes (see Fig. 2.1). Note that the horizontal canals of the two ears lie in the same plane, while the superior canal of the left ear is coplanar with the posterior one of the right ear and vice versa.

The three semicircular canals have very nearly the same structure and dimensions. Each canal starts at the utricle, forms approximately 2/3 of a circle with outer diameter of 4 to 6 mm, dilates at the ampulla, contracts again, and terminates at the other end of the utricle. The canals have five orifices to the utricular sac, since the posterior and the superior canals have a common duct along the intersection line of their planes. The ampulla is nearly sealed by the ampullary crista and the cupula. The crista contains supporting hairs and sensory cells which project into the cupula, a domelike gelatinous mass (77). (See Fig. 2.3.) The cupula is of equal density to the endolymph which fills the narrow (0.3 mm in diameter) semicircular canals. In contrast to the structure of the utricle and the saccule, there is no interspace between the crista and the cupula, although sliding movement of the cupula is feasible.

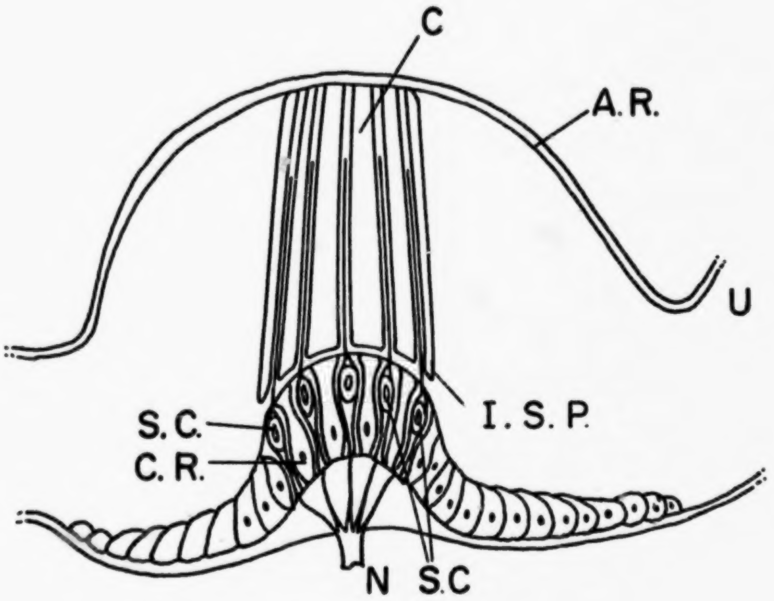


Figure 2.3. Schematic Drawing of a Cross Section Through an Ampulla and Crista

A R, ampulla roof. C R, crista, consisting of S C (sensory cells), supporting cells, and N (nerve fibres). Between cupula and crista there is the I S P (intercupular space). U, utricle (77).

The semicircular canals are heavily damped, angular accelerometers. Their arrangement in three perpendicular planes provides a way to sense components of angular acceleration along three axes which are amenable to easy vectorial manipulation.

The vestibular nerve sends a branch to each crista of the canals and the utricular macula, while two branches are imbedded in the saccule. The transmission of information from the vestibular sensors to the central nervous system is by frequency modulation. When unstimulated, the sensors show nerve action potentials of about 8 to 10 pulses per second (pps). For the semicircular canals, the firing rate will increase or decrease according to the direction of the input angular acceleration and in proportion to its strength. Similar responses may be recorded for the utricular macula but without clear directional response.

The physiology and topology of the labyrinth throw some light upon its sensory characteristics. The fact that the semicircular canals have their mean planes very nearly perpendicular allows three-dimensional sensing of angular accelerations. Since the canals open into the utricle, interaction between canals is plausible by virtue of endolymph flow. Moreover, the posterior and the superior canals share a common duct. Thus they are stimulated to a different degree, perhaps, but simultaneously. The dynamic characteristics of the canals depend upon the specific density of the cupula and the endolymph, and would alter if the cupula does not seal the ampulla while deflected.

To summarize, the anatomy of the labyrinth displays two different groups of sensors. Their structure is distinctly different, as are their sensory functions.

Orientation-Reference Coordinates

The location and the mean planes of the vestibular sensors, as well as their attitude in the head is known. Thus the geometric coordinates of the vestibular system are unique in any given head axis system. Because there is no relative motion between the head and the labyrinth sensors, head movements can be referred to as inputs of the vestibular system. Consequently, a head fixed, axes frame, which considers the symmetry of the labyrinths, is a convenient coordinate system to define in it the accelerations acting on the skull.

Two perpendicular planes are defined for the head, the frontal plane and the sagittal plane. The latter divides the head into two symmetrical halves and contains the sagittal X_h (fore and aft) axis and the vertical Y_h axis. The intersection of the frontal and the sagittal planes form the vertical axis such that it runs colinear to the gravity vector. If the origin of the head coordinate system is located between the labyrinths, the sagittal axis, for an erect head, will run horizontal, and the vertical axis is along the neck (see Fig. 2.4). The lateral axis, Z_h, completes the right-handed coordinate system. Note that the frame defined here is related to the functional planes of the sensors by a single transformation through an alignment matrix $[\delta]$.

Orientation of the body is defined with respect to a given system of coordinates--the reference system. Dynamic orientation is then the ability to determine the relative motion between the head axes system and the reference coordinates. The natural selection of the reference frame (X_e, Y_e, Z_e) is to have it coincide with the head axes for normal unaccelerated body posture. These earth-fixed axes do not rotate or translate.

The issue of normal posture refers to the relative position of the head with respect to the trunk. Absence of bending or torsion of the neck is a normal configuration of head and body interconnection. In this context, suspension of the body upside-down, with the head free, is still an acceptable posture.

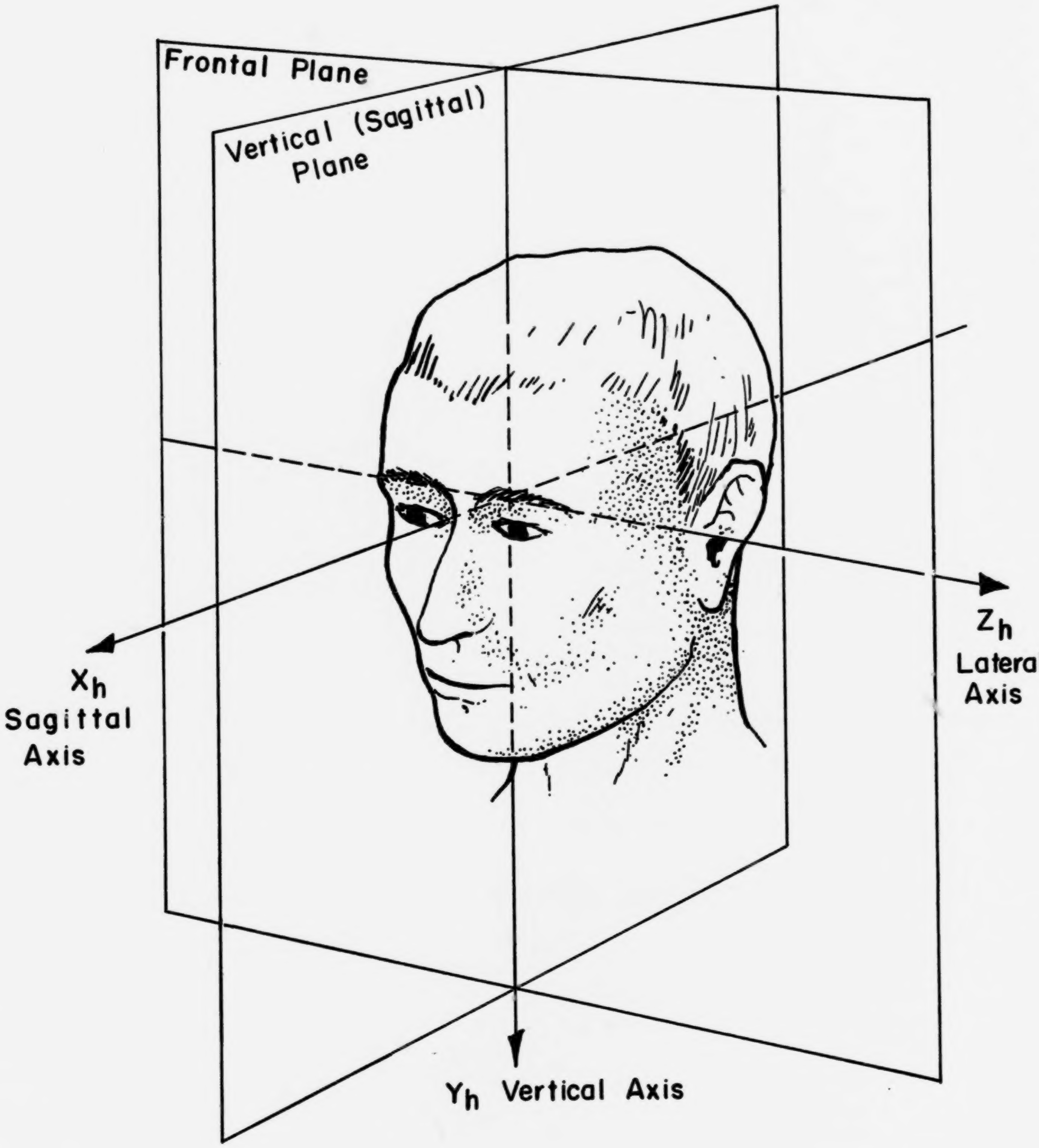

Frontal Plane
Vertical (Sagittal) Plane
Z_h Lateral Axis
X_h Sagittal Axis
Y_h Vertical Axis

Figure 2.4. The Head Planes and the Head Axis System

Control Variables

The vestibular sensors are sensitive to accelerations, thus the input variable to the vestibular system is a vector having direction and magnitude. The output quantity, however, is not a vector in the strict sense. Information from the semicircular canals and the otoliths is sent to the central nervous system and thereafter an awareness of the sensation of motion is perceived. This perceived output variable preserves the indication of direction like a vector. However, sense of magnitude is applicable only on a comparative basis, where motions are faster or slower without an absolute scale. It is unusual to assign a perceived variable as an output of a control system, particularly when it only resembles the input. Nevertheless, perceived orientation is the most important sensation the human experiences in response to an input acceleration and will be considered here as the output of the vestibular system. There are also some objective measurements of activity of the vestibular sensors, the most known ones being observations of compensatory eye movements. However, those are derived variables with some transfer characteristics related to the output of the vestibular sensors.

In conclusion, the vestibular system should be examined as a sensory complex of accelerometers with certain dynamic characteristics which establish the input-output relations between accelerations applied in the head axes frame and perceived orientation as indicated by the human.

Identification Processes

In humans, identification of sensing capabilities of the vestibular system is associated closely with experiments of psychophysical nature. Validity and usefulness of experimental work of this kind depends on the correlation one can draw between the precise, and usually well defined, input conditions and the human response.

Control engineering theory offers a number of identification techniques where only yes and no types of responses will suffice. For a step or an impulse input, indication of onset of perception or termination of it contains the pertinent data on the characteristics of the sensor. Standard frequency response for a linear system required only phase lag or lead data to identify the time constants of the system.

Stimulation of the vestibular system is a source of various illusions which the human interprets as a subjective orientation. For identification purposes, these illusions are an excellent tool to obtain the time course of a sensation or a steady state value (gain and sensitivity) of a transfer function. The objective measurements of vestibular activity, such as measurement of eye movements, is probably the most effective and reliable method of response identification. As noted before, compensatory eye movements indicate stimulation of the semicircular canals. However, the relation between these movements and the dynamics of the canals has to be determined by comparison with psychophysical experiments.

Finally, identification techniques suitable for manual control systems could be applied to the vestibular sensors. If the experimental subject (human operator for these conditions) is placed in an orientation control loop with the function of a sensor and a controller assigned to him, the system response can be analyzed in terms of control characteristics of equivalent "black boxes." The block corresponding to the human operator will indicate the intrinsic dynamics of his sensors and the effects of data processing by the central nervous system.

3. THE SEMICIRCULAR CANALS

The semicircular canals are the rotational sensors of the vestibular system. When stimulated, they participate in the control of the postural reflexes of the body and initiate compensatory eye movements in order to preserve the body balance and reference with respect to the environment. Consciously, the human is aware of the rotations his head undergoes. The information on orientation the human can obtain from his semicircular canals can be analyzed by control engineering methods and summarized in a mathematical model describing the dynamic characteristics of the three semicircular canals.

Input Vector and Sensitive Axis

Rotation of the head has been identified as the motion which stimulates the semicircular canals. Another observation indicates that the canals cease to show activity during prolonged periods of rotation with constant angular velocity. The conclusion is that the semicircular canals are sensitive to angular accelerations, which are applied about an axis normal to the plane of the canal. Because there are three semicircular canals in each ear, input accelerations are sensed along three mutually orthogonal axes and probably summed vectorially in the central nervous system.

When the canals are stimulated, the human is consciously aware of a rotational motion, a perceived sensation of rotation. Furthermore, the time course of the perceived sensation will depend upon the dynamic behavior of the canals, which can be simulated by a simple mechanical model.

A Physical Model for the Semicircular Canals

The theory of operation of the semicircular canals was first set by Steinhausen and is based on the concept of a heavy damped torsion pendulum for the cupular mechanism (154). In this model, the fluid ring of the canals corresponds to the moment of inertia of the pendulum and the spring restoring torque is provided by the elasticity of the cupula. The heavy damping is attributed to the viscous torques arising from the flow of the endolymph through the capillary canals (157). (See Fig. 3.1.) This theory is based on the assumption that over a certain range of angles the cupula deflects while still sealing the ampulla. The assumption of a pendulum model indicates that the cupuloendolymph system will obey a second order linear differential equation first formulated by van Egmond, Groen, and Jongkees (157). As shown in Figure 3.1, the cupula deflection is assumed equal to the angle of rotation of the endolymph. This assumption approximates the canals to a tube with a constant, cross sectional area. The angular deviation of the cupula with respect to the skull is given by

$$I\theta + B\theta + K\theta = I\alpha \tag{1}$$

where I = moment of inertia of the endolymph; B = viscous damping torque, at unit angular velocity (rad/sec) of the endolymph with respect to the skull; K = stiffness, torque per unit angular deflection of the cupula; θ = angular deviation of the cupula with respect to the skull (rad); θ = angular velocity of the cupula with respect to the skull (rad/sec); θ = angular acceleration of the cupula with respect to the skull (rad/sec^2); and α = input angular acceleration along the sensitive axis of the canal (rad/sec^2).

Equation (1) represents the time response of the cupula, in any given semicircular canal, as a function of the input stimulation. The response is seen to depend upon two parameters: B/I and K/I.

Rotation About the Vertical (Y_h) Axis

The reference frame of orientation and the head axes were assumed to coincide for a nonmoving, erect head. For these initial conditions, rotation of the head about the earth-fixed vertical axis (Y_e) stimulates the semicircular canals sensitive to accelerations about the Y_h axis. The tangential and centrifugal accelerations associated with this rotation are below the threshold of perception of the otoliths. If angular accelerations are applied about the Y_e (and Y_h) axis, the parameters of the canals can be determined without interference effects from the linear acceleration sensitive otoliths.

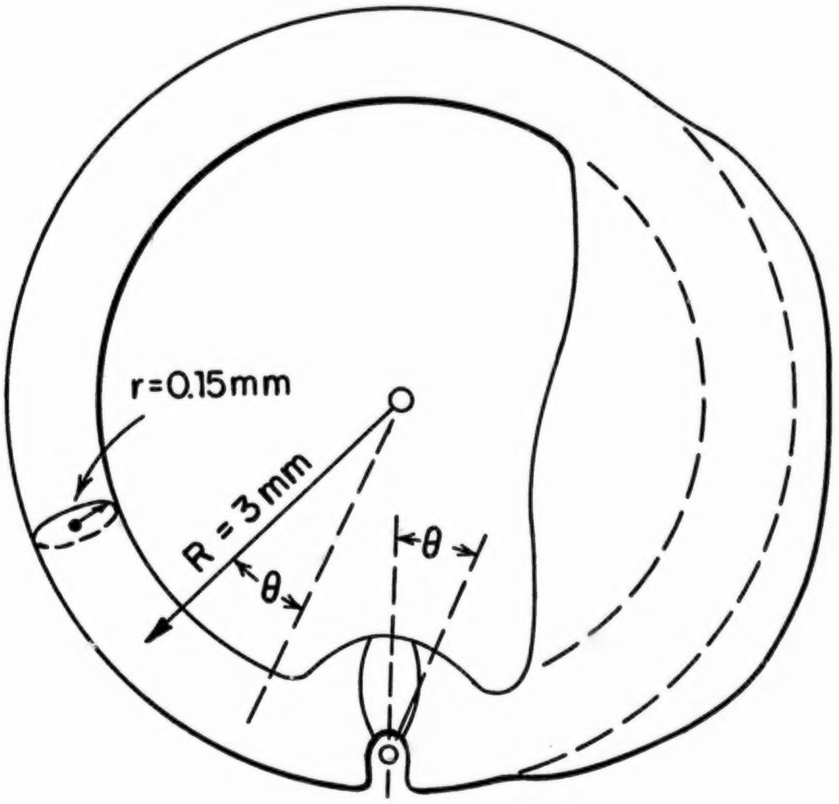


Figure 3.1. Schematic Diagram of the Semicircular Canal (157)

The second order characteristic equation for the canals (Eq. 1) has two roots, ω_1 and ω_2:

$$\omega_{1\text{ and }2} = \frac{\frac{B}{I} \pm \sqrt{\frac{B}{I}^2 - 4\frac{K}{I}}}{2} \tag{2}$$

However, since the viscous torque is very high compared to the elastic one, an assumption has been made that $K/B \ll B/I$, yielding two real roots:

$$\begin{aligned} \omega_1 &\cong -\frac{K}{B} \\ \omega_2 &\cong -\frac{B}{I} \end{aligned} \tag{3}$$

The transfer function of the canals, from angular acceleration about the head vertical axis (α_{Y_h}) to cupula position (θ) is given by

$$\frac{\theta\ (s)}{\alpha_{Y_h}\ (S)} = \frac{1}{(s + \omega_1)(s + \omega_2)} \qquad (4)$$

where s = the Laplace transform operator.

The time constants of the cupular model B/K and I/B are widely separated, thus imposing a certain difficulty on their experimental evaluation. Van Egmond *et al.* established the values of those time constants within 10 to 20 percent allowance for experimental errors (157). Their assumption is that the perceived sensation of angular velocity is related to the cupula deflection. According to this assumption, measurements taken on parameters of perceived sensations correspond to the parameters of the cupular model.

The duration of a transient response of the cupula to a velocity step, plotted against the magnitude of the step input is called by van Egmond "subjective cupulogram." Indeed, measurement of duration of perception as reported by a subject is one reliable method to determine the value of B/K. The core of the method relies on the instantaneous stop of a platform moving with constant angular velocity and subsequently recording the time of sensation reported by the subject. Mathematically, for a step of ∂°/sec, the time response of the cupula, initially at rest will be

$$\Theta(t) = \partial (I/B) \left[e^{-(K/B)t} - e^{-(B/I)t}\right] \qquad (5)$$

Physically, due to the angular momentum imparted to the endolymph and the viscous torque, the cupula is deflected to a certain maximum angle following which it slowly returns to zero under the influence of its own elastic torque opposed by viscosity. The sensation the subject reports during the process, is of rotation in the direction of the input step with slowly decreasing velocity. The return phase of the cupula will exhibit simple exponential decay

$$\theta\ (t) = \partial (I/B) e-(K/B)t \qquad (6)$$

since the term e of equation (5) is $e-(B/I)t<<1$.

The sensation of rotation the subject perceived, will stop, the moment the cupula reaches a deflection Θ_{min} (theta minimum) which corresponds to the deflection for threshold of perception. Then, the approximate time for this event will be:

$$t = B/K \log \left[(I/B)(\partial/\Theta_{min})\right] \qquad (7)$$

or

$$t = B/K \log\ (I/B\theta_{min}) + (B/K) \log \partial \qquad (8)$$

A series of time measurements for angular velocity step responses plotted on semilogarithmic scale will yield the time constant B/K = 10 sec (157). (See Fig. 3.2.)

Besides testing for transient response, the cupular model for the semicircular canals can also be studied in the transformed frequency domain. The increasing phase shift of subjective sensation of angular velocity with respect to the input acceleration is an indication reflecting the time constants of the model. Consider an input sinusoidal rotation with frequency $\omega_0 = K/I$, the undamped natural frequency of the cupular model. For this input the angular deflection of the cupula lags the input acceleration by 90°. Thus, the cupula is in phase with the input angular velocity, which is zero at the peaks of the rotation. At these instances, the subjective feeling will be that of rest. Experimenting with a torsion swing, van Egmond found that

$$\omega_0 = 1.0 \text{ rad/sec} \qquad (9)$$

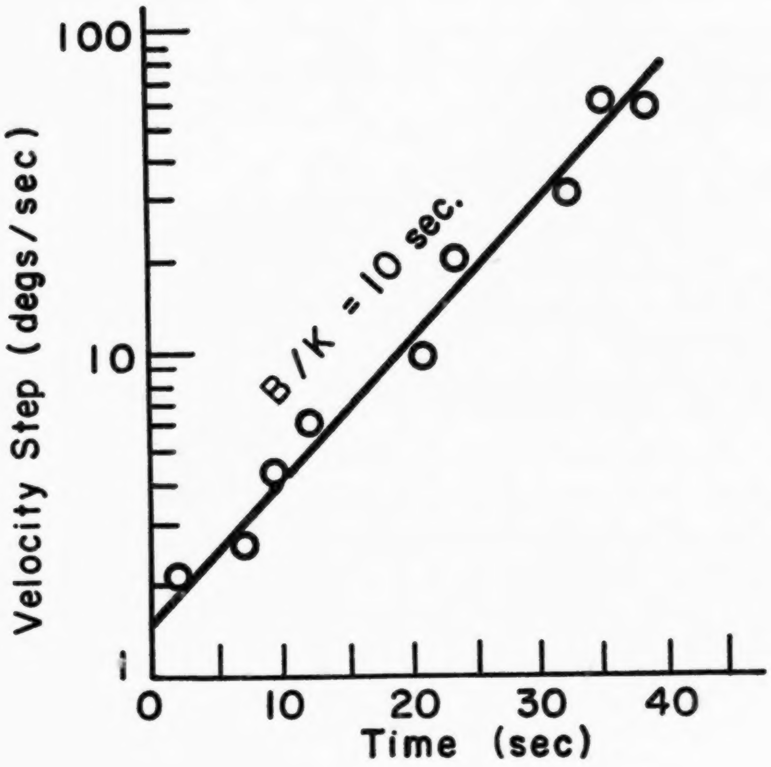


Figure 3.2. Duration of Sensation As a Function of the Velocity Step Input

With this result, the second time constant, I/B, of the cupular model is evaluated as

$$I/B = (1/\omega_0)(K/B) = 0.1 \text{ sec} \tag{10}$$

With the proper values of time constants, the transfer function for the semicircular canals as given in Eq. (4) corresponds to

$$\frac{\theta\ (s)}{\alpha_{Y_h}\ (s)} = \frac{1}{(10s + 1)(0.1s + 1)} \tag{11}$$

Equation (11) indicates that the steady state angle of the cupula, subjected to stimulation of constant angular acceleration is $\theta_{(t=\infty)} = \alpha_{Y_h}$. The assumption can be verified by using the velocity step response test in conjunction with subjective estimation of total angular travel. When van Egmond instructed his subjects to report completion of full revolutions, the experimenter could determine the average subjective velocity for the subject. Indeed, the indication confirmed decay with a time constant of $B/K = 10$ sec. However, when the velocity was extrapolated to its initial value, it agreed absolutely with the applied step of angular velocity (157). (See Fig. 3.3.) This finding brings to the modification of the cupular transfer function when associated with subjective perception of angular velocity such as

$$\frac{\text{subjective angular velocity } (s)}{\alpha_{Y_h}(s)} = \frac{10}{(10s + 1)(0.1s + 1)} \tag{12}$$

Note that the parameters of the cupular model and the associated transfer function as presented in Eq. (12) were tested for subjective perception. This is in agreement with the definition of a transfer function for the vestibular sensors where the output variable is perceived sensation.

The time constants of the cupular model for input accelerations about the vertical head axis, especially the long one, can be measured by objective methods based on the compensatory eye movements elicited during periods of stimulation of the canals. Section 4 will discuss the relations between the semicircular canals and the eye motor system. Another identification method, dealing with an illusion of vestibular origin is examined under Habituation, later in this section.

Pure theoretical attempts to estimate the parameters of the semicircular canals are based on approximating them to circular tubes with viscous flow in it. The results show a time constant of $B/K = 27$ sec, which is much higher than measured experimental values.

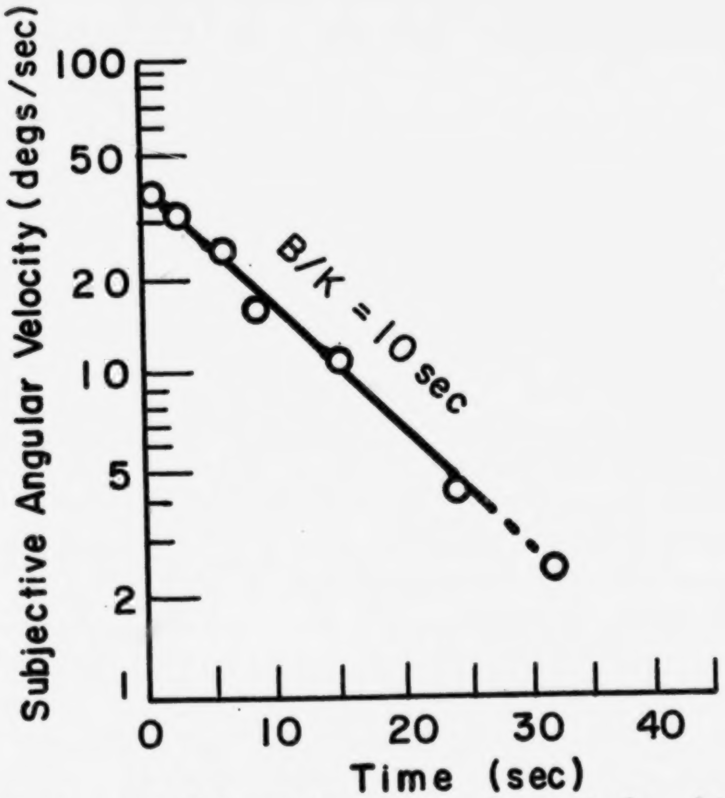


Figure 3.3. Subjective Angular Velocity After a 40°/sec Velocity Step

Threshold of Perception. Studies of human perception of angular acceleration indicate the phenomenon of threshold. At the threshold, or below it, the existence of a constant input acceleration for prolonged time will not be noticed. Physically, the threshold is associated with the minimal deflection of the cupula which will lead to a conscious sensation of rotation. The time from the onset of the input until it is perceived, the latency time, will be a function of the magnitude of the input vector, and the dynamics of the sensor.

A technique utilizing the step response in acceleration of the semicircular canals is widely accepted as a subjective measurement of threshold (32). The method applies a known constant angular acceleration to the subject and his latency time is recorded. The step response of the semicircular canals to an input acceleration about the vertical axis Y_h is

$$\theta(t) = \alpha_{Y_h} + \frac{\alpha_{Y_h}}{10 - 0.1}\,(0.1e^{-10t} - 10e^{-0.1t})$$

$$\cong \alpha_{Y_h}\,(1 - e^{-0.1t}) \qquad (13)$$

where α_{Y_h} = input angular acceleration, °/sec^2. Consequently, if $\theta_{\min}$ is the deviation of the cupula at the threshold,

$$\theta_{\min} - 0.1\alpha_{Y_h}\,\tau\,(1 - \frac{0.1\tau}{2} + \frac{0.01\tau^2}{6} - \ldots) \qquad (14)$$

with τ latency time, sec.

The product $\alpha_{Y_h}\tau$ is called by van Egmond *et al.* the "Muelder product," and their observations showed it approximately constant and equal to 1.5 to 2.0°/sec over the range 1 to 5°/sec^2. If the "Muelder product" is constant, it implies that the product of latency time and input acceleration will remain constant for a certain range of input accelerations.

However, the applicability of the "Muelder product" is limited to regions where the additional terms of the series in Eq. (14) do not exceed say 10 percent, or $\tau \leq 2.5$ sec. The controversy about the validity of the product for accelerations about the threshold when latency times are longer than 2.5 sec is indeed well founded as Eq. (14) shows (47).

The validity of the "Muelder product" over the range of accelerations from 0.1°/sec^2 to 10°/sec^2 was tested by the author. The step response technique for measuring threshold of perception was used to measure latency time. The subjects, seated in a hooded cab of a moving base simulator, were administered constant angular accelerations about the earth-fixed vertical axis (Y_e) with random order in direction and magnitude, six readings at any given acceleration. Headrest and support for the back of the subject kept his head erect under the axis of rotation and with no strain to the neck muscles. Perceived rotation was measured by a "forced choice" method: the subject had to manipulate a control stick indicating the direction of movement, as well as the onset of his subjective detection of rotation. The experimental sequence provided 30 seconds of rest between consecutive runs. Three subjects were used for these experiments.

Figure 3.4 presents the experimental results averaged over the three subjects, along with the expected latency time computed from Eq. (14). The expected latency time curve was computed relative to the experimental value at $\alpha_{Y_h} = 1.0$°/sec^2. A perfect agreement between latency times predicted from Eq. (14) and measured values is found over the region of angular accelerations from 0.3 to 5°/sec^2. Near the threshold (about 0.14°/sec^2 determined on 75 percent correct identification of input direction), the departure from theoretical results is probably due to scatter in the data caused just by the fact that measurements are taken near the limit of detection. Similarly, when latency times approach the response time of the human, the experimental data shows longer latencies than predicted. Results obtained for pilots by Clark and Stewart (32) using identical techniques are also presented in Figure 3.4. There is no significant difference between results measured with those subjects (pilots) and the subjects, with no flying experience, used here. The mean latency times measured here

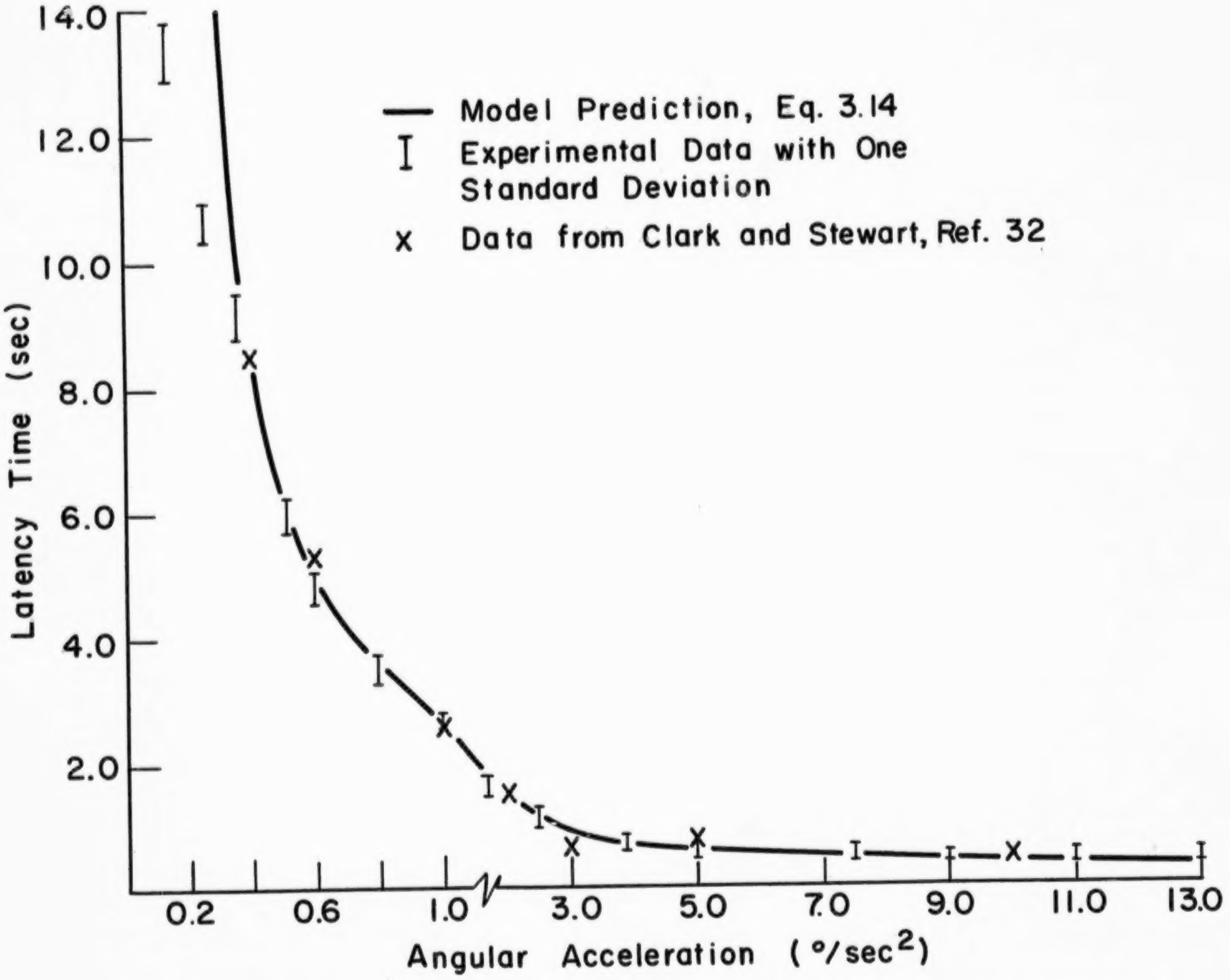


Figure 3.4. Latency Times for Perception of Angular Acceleration About the Vertical Axis (Y_h)

(Note: scale change of angular acceleration)

are also presented in Figure 3.5. Plotted on a log-log scale, the "Muelder product" is a line with slope of -1. Examination of Figure 3.5 indicates the region of validity for this product. As noted before, the product $\alpha_{Y_h}\tau$ = constant is not a valid approximation while the input angular accelerations are smaller than 1.0°/sec^2. Additional terms from Eq. (14) improve the correspondence between measured and expected latency times.

On the basis of this series of experiments, the following conclusions are justified:

1. The threshold for perception of angular acceleration around a vertical axis will vary subjectively between 0.1 and 0.2°/sec^2 with a mean of about 0.14°/sec^2.

2. Latency times for detection of small accelerations can be predicted accurately from the model for the semicircular canals.

3. For its range of validity ($\tau \leq 2.5$ sec) the "Muelder product" holds with somewhat higher value (2.6°/sec) than usually reported.

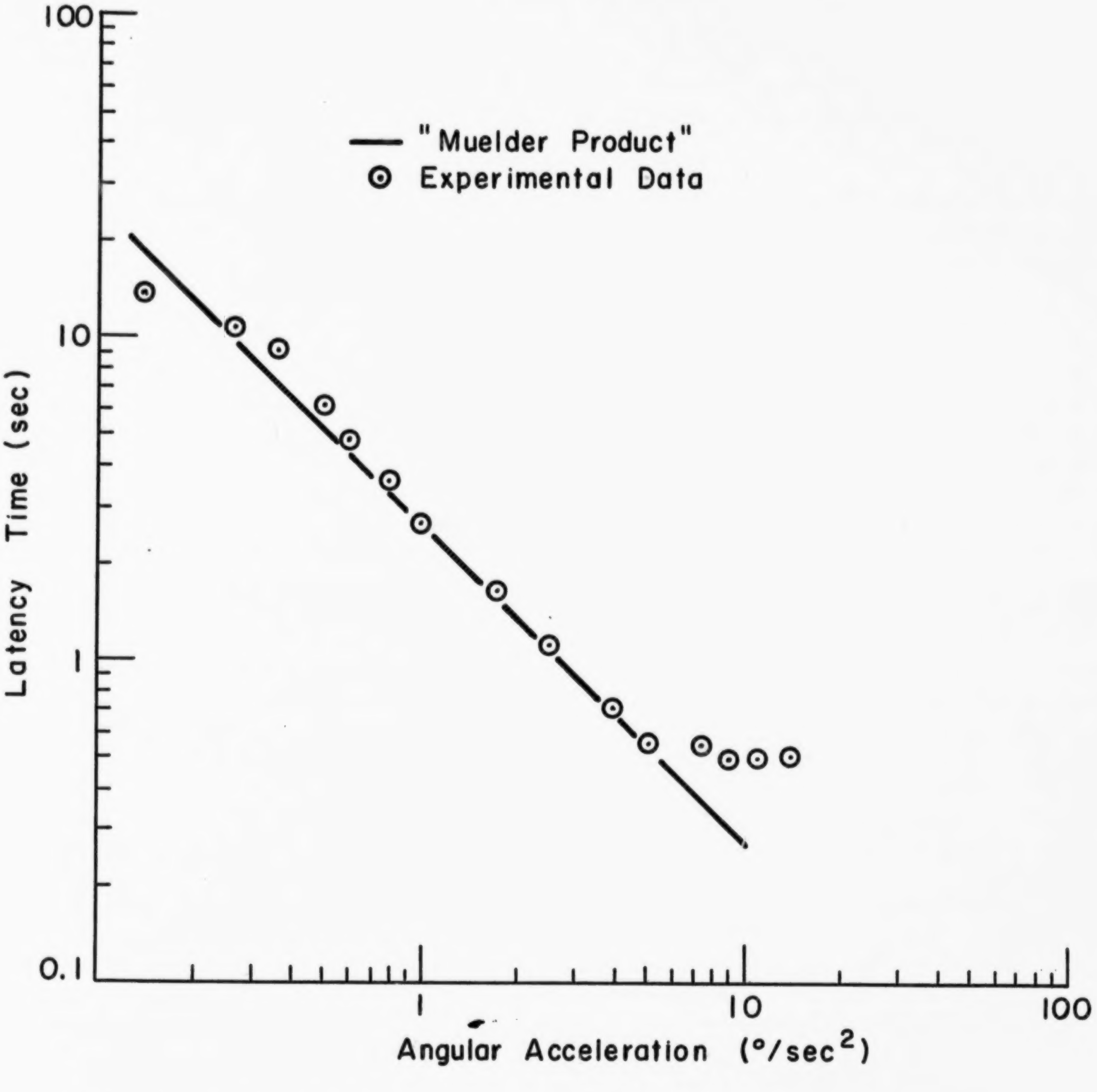


Figure 3.5. Latency Times for Perception of Angular Acceleration About the Vertical Axis (Y_h)

Habituation

Objective measurements of the semicircular canals' activity by recording compensatory eye movements and subjective cupulograms indicate changes in response due to frequent stimulation. The phenomenon is called habituation, pointing to a variation of parameters according to the recent history of stimulation for the canals. Indeed, the question is raised whether certain characteristics of the sensors measured at any given time are not heavily influenced by the experimental methods used to obtain these results.

Differences are reported between subjective cupulograms and cupulograms for objective, compensatory eye movements. Moreover, the habituation effect becomes pronounced, for a given technique, while the experimental pattern is repeated several times. For the vestibular system, the output vector has been defined here as subjective perception of angular velocity. Similarly, the focus should be on time variations found for the parameters of the semicircular canals measured by subjective indication. Values for B/K obtained by the repetitive technique of subjective cupulometry show $B/K = 8$ to 10 sec (77). Those observations will pertain as long as the semicircular canals are not exposed to continuous stimulation lasting for several hours, at which time a gradual decrease of the time constant is found (77). However, a period of rest restores the cupulogram to its original value, regardless of the level reached prior to it. This evidence is sufficient to conclude that the physical model of the semicircular canals and the experimental values attached to its parameters, represents the expected, average response of a human living in an environment which does not impose stimulation beyond "normal." In this context, normal stimulation can be defined as exposure to rotations necessitated by everyday life. The response of the canals is probably adapted to living conditions on earth, similar to the way habituation takes place when those conditions are changed.

Objective cupulograms measuring the velocity of the slow phase of vestibular nystagmus find $B/K = 16$ sec. Those responses will hold for stimulation periods well beyond the time when effects are noticed on subjective measurements. However, for professionals with constant exposure to angular accelerations, like figure skaters and pilots, the objective cupulograms show the habituation phenomenon along with the accompanying recovery from it.

The habituation to stimulation is in general attributed to the central nervous system (52, 77). This notion on habituation is supported by the fact that compensatory eye movements, being of a somewhat reflex nature, do not adapt easily. Indeed, for very sensitive subjects, objective and subjective cupulograms agree numerically, indicating adapted response for most of the subjects, randomly selected (77). Still, neither the mechanism of habituation nor the periods of time involved are known.

Experiments on cats stimulated repeatedly with sinusoidal rotation of one given frequency show marked habituation of compensatory eye movements to this particular frequency while effects taper off for the adjacent spectrum of frequencies (41). These findings support the notion that habituation is central, since it is hard to attribute mechanical fatigue of the canals to a certain frequency only. However, as stated before, besides identifying the phenomenon, no control description can be attached to it yet.

In an effort to overcome the effect of habituation on the long time constant of the semicircular canals, Cawthorne *et al.* used the oculogyral illusion to indicate the time response of the cupula in response to an impulse of angular acceleration (18). During the oculogyral illusion, a light which is stationary with respect to the subject, will appear to him as moving with him in the direction of motion of the subject. The illusion has been explained to be due to the compensatory eye movements, thus acceleration to the left produces eye rotation to the right and an accompanying motion of the visual target opposite to it. The velocity of the oculogyral illusion in response to an impulse of acceleration, as obtained by Cawthorne, shows a time constant, B/K = 24 sec. However, at present it is not completely clear whether the oculogyral illusion originates solely in the vestibular system. Therefore, parameters measured by this method are still questioned.

Rotation About a Horizontal Axis

Investigators have assumed that the torsion pendulum model for the cupula deflection is valid for rotation about any head axis. However, experimental efforts to validate this assumption and to determine the time constants of the model [see Eq. (3)] were undertaken almost exclusively for rotation around the vertical head axis (Y_h). The deterrent is, of course, the difficulty to produce rotation about a horizontal axis (pitch or roll) without stimulating the linear motion sensors of the vestibular system.

In the literature, two experiments are reported to measure the long time constant, B/K, in perception of rotation about the sagittal and the lateral axes of the head (102, 108). Neither of these experiments preserved the normal head-neck posture as discussed in the first section; thus results are possibly affected by proprioception. The angular accelerations were applied about the earth-fixed vertical axis with the head tilted to reach the proper head axis. Jones *et al.* recorded by subjective cupulometry for roll, $(X_h)(B/K)$ = 6.1 sec, and for pitch, $(Z_h)(B/K)$ = 5.3 sec. From eye movement evaluation of response to a single velocity step input, the corresponding values are B/K = 6.6 sec and B/K = 4.0 sec, respectively (102).

With a similar technique of stimulation, Ledoux used the data on the topography of the vestibular system to stimulate each coplanar pair of canals by accelerations about an axis perpendicular to its mean plane. Objective cupulometry in planes parallel to the planes of the canals did not show variations of characteristics among the three pairs of semicircular canals (108).

No data on the short time constant I/B and the sensitivity of the canals stimulated in pitch and roll is available. Nevertheless, it is plausible to assume them as equal to those for rotation in yaw.

Threshold of Perception (Experiment by the Author). Using the technique of applying steps of angular accelerations and recording the latency time until rotation is perceived, the threshold of sensation for rotation around the head sagittal axis (roll) was determined. The measured latency times for perception of small accelerations were used to obtain the long time constant, B/K, of the canals sensitive to angular accelerations about this axis.

The experimental method and procedure were identical to those described earlier. The point to note is that the simulator cab was rotated about the earth-fixed vertical axis (Y_e). The subject seated, was accommodated to rest his head, face down, on a head rest under the axis of rotation of the simulator. By bending the body at the waist rather than the neck, the "normal" posture of head-neck, or a position within a few degrees from it was preserved throughout the experiment.

Under these circumstances, the vestibular linear motion sensors were not stimulated during the experiment except for the steady change of orientation of the head with respect to gravity. The tangential and centrifugal accelerations here are below the threshold of these sensors.

The experimental results are presented in Figure 3.6. Threshold of perception is found approximately at 0.5°/sec^2 angular acceleration and a rather sharp separation between sensation and lack of it is noted. The mean latency times, averaged over the three subjects were used to estimate the long time constant of the semicircular canals in this configuration. Making the assumption that the short time constant is 0.1 sec and fitting an equation of the form of Eq. (14) to the data yields $B/K = 7$ sec. Latency times measured in these experiments were compared with results from responses for rotation around the vertical head axis (Y_h) and the difference between the mean values were found highly significant ($P \leq 0.005$) for accelerations lower than 5.0°/sec^2. Assuming the short time constant of the sensors as 0.1 sec and an agreement between the subjective and the input velocity over the range of 0.14 rad/sec to 10 rad/sec will yield the following transfer function:

$$\frac{\text{Subjective angular velocity } (s)}{\alpha_{X_h}(s)} = \frac{7}{(7s + 1)(0.1s + 1)}$$

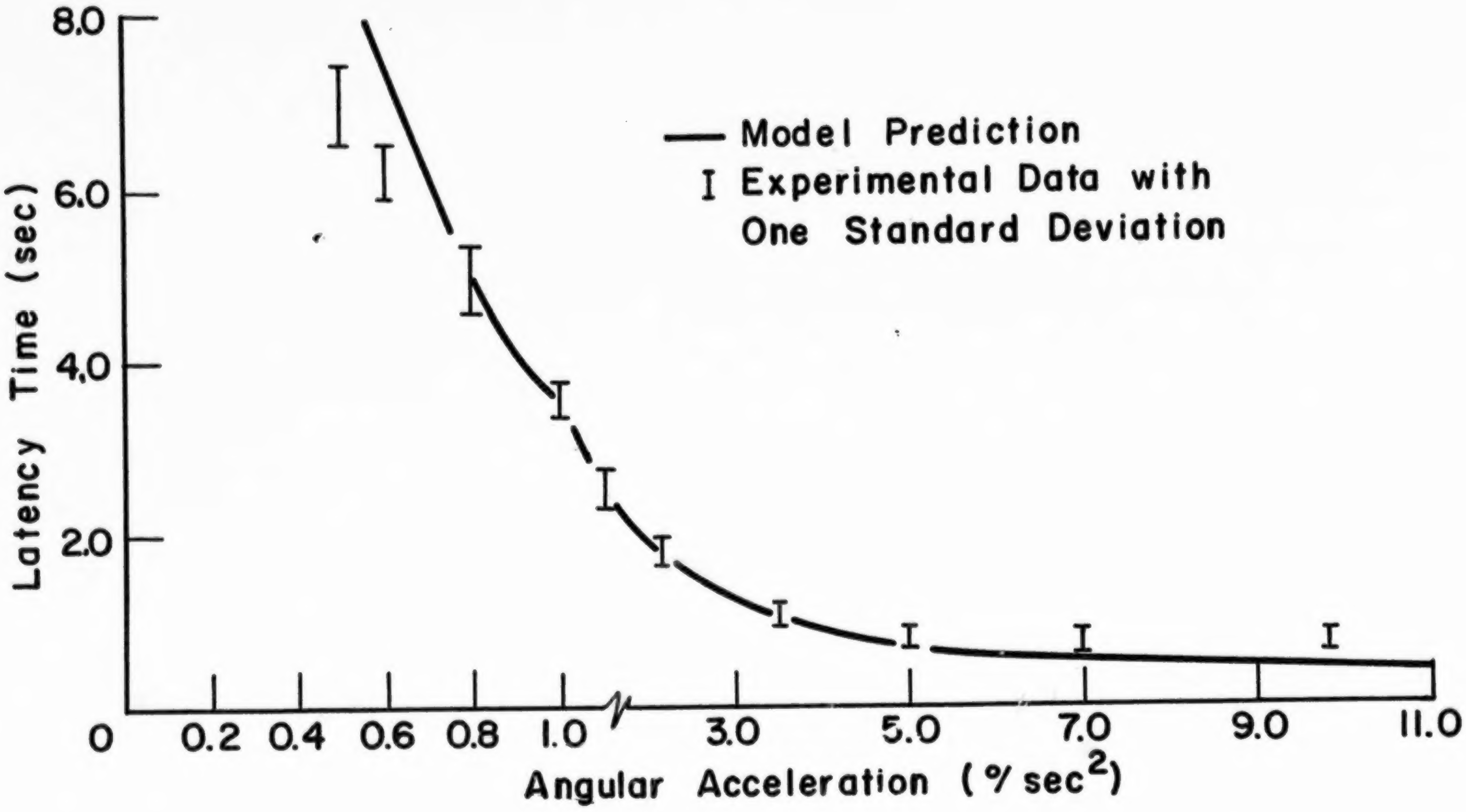


Figure 3.6. Latency Times for Perception of Angular Accelerations About the Roll Axis (X_h)

(Note: Scale change of angular acceleration.)

A Mathematical Model for the Semicircular Canals

The experimental data presented in this chapter reflects certain characteristics of the semicircular canals which can support a state of knowledge mathematical model for this portion of the vestibular system (8). The block diagram in Figure 3.7 shows the dynamic characteristics of the canal system and the physiological organs to which they are attributed. Angular accelerations measured in the earth-fixed frame (α_e) are resolved into components in the head axis system by the orientation matrix [A], which is dependent upon the orientation of the skull. In the semicircular canals, stimulated by the input acceleration, the cupula deviates from its null position in agreement with the highly damped second order model. When the cupula deviation exceeds the threshold level, this information is picked up by the central nervous system to be interpreted consciously as subjective angular velocity. Note that this model is not representing characteristics of any given canal, neither is it associated with stimulation of physiological synergic (acting together) pairs, but outlining perception of accelerations in the head axis system as defined in the second section. As presented here, the dynamics of the canals associated with

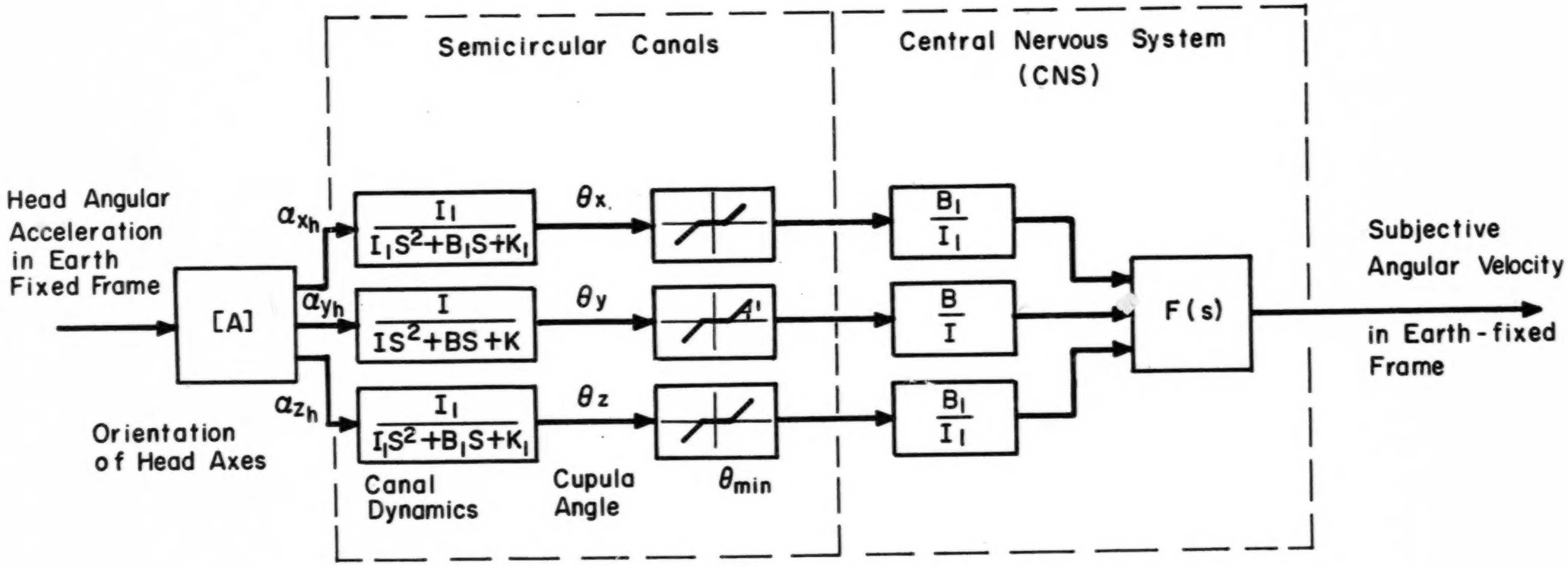

Semicircular Canals
Central Nervous System (CNS)
Head Angular Acceleration in Earth Fixed Frame
[A]
Orientation of Head Axes
α_{x_h}
α_{y_h}
α_{z_h}
$\frac{I_1}{I_1S^2+B_1S+K_1}$
$\frac{I}{IS^2+BS+K}$
$\frac{I_1}{I_1S^2+B_1S+K_1}$
Canal Dynamics
θ_x
θ_y
θ_z
Cupula Angle
A'
θ_{min}
$\frac{B_1}{I_1}$
$\frac{B}{I}$
$\frac{B_1}{I_1}$
F(s)
Subjective Angular Velocity in Earth-fixed Frame

Figure 3.7. Semicircular Canal Block Diagram--Short Period of Stimulation

perception of angular accelerations about the X_h and Z_h axes (roll and pitch) are assumed to be equal. The central nervous system, CNS, is shown here as a block $F(s)$ to underline the fact that certain unknown transfer characteristics are associated with it. As discussed previously, habituation is a control process attributed to CNS. When the semicircular canals are not affected by excessive stimulation, the perceived sensation of rotation is assumed to depend entirely upon the canal dynamics thus rendering $F(s) = 1$.

What is the physical vector that corresponds to the subjective perception of angular velocity? This question is concerned with the mental evaluation of information provided by the semicircular canals. Figure 3.8 is the frequency response of the canals (Bode plot) for rotation about the vertical head axis (Y_h)

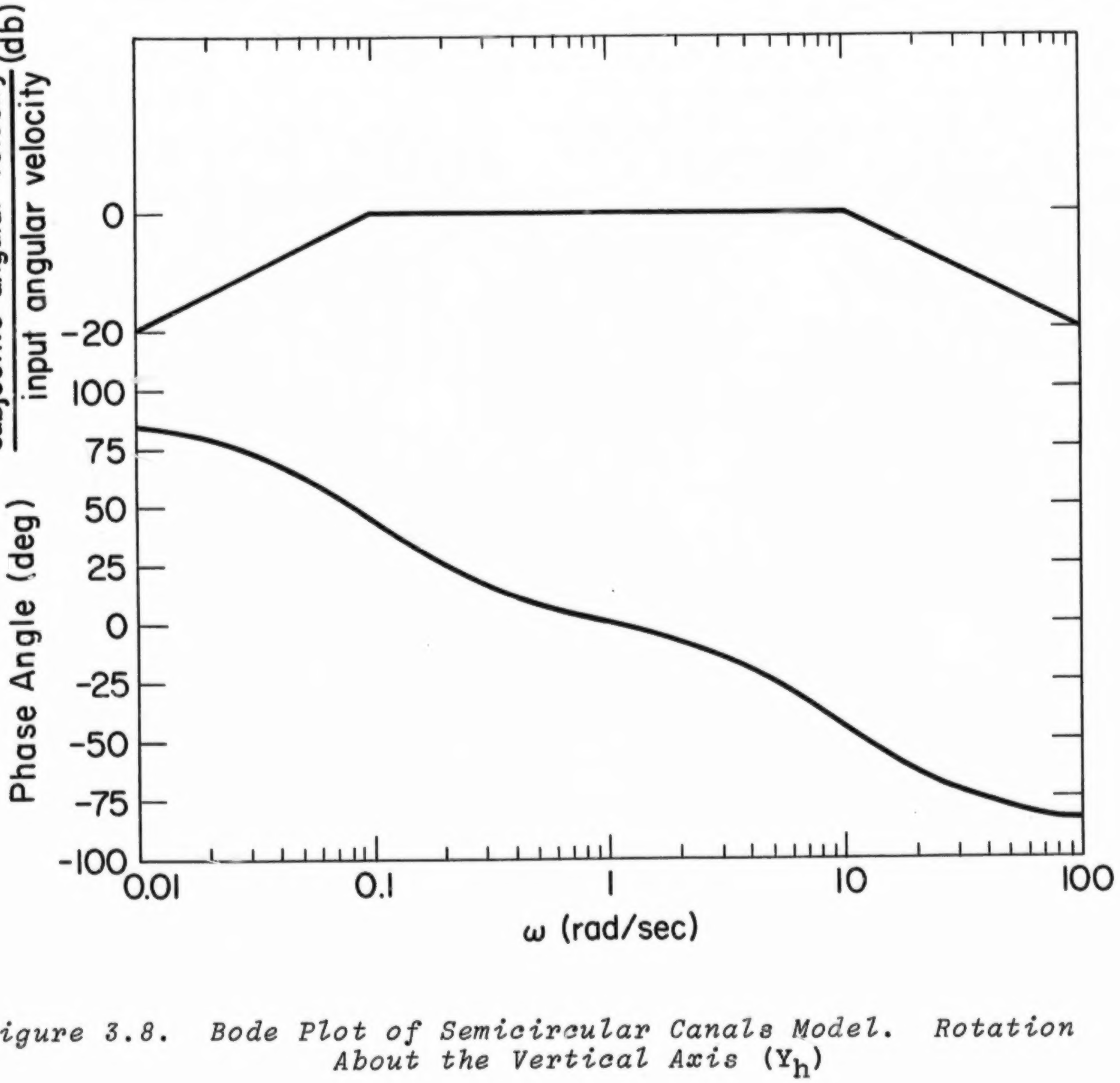


Figure 3.8. Bode Plot of Semicircular Canals Model. Rotation About the Vertical Axis (Y_h)

with the input vector being the angular velocity of rotation and the output is the subjective perception of angular velocity assumed proportional to the cupula deflection. Note that over a wide range of frequencies, namely 0.1 to 10 rad/sec, the subjective sensation is that of the angular velocity of the motion. Similar observations hold for perception of angular velocities about the horizontal axes although with a slightly condensed frequency range, thus rendering the semicircular canals as angular velocity meters over most of the frequency spectrum of head movements during everyday activity. Moreover, while a rotation with constant angular velocity will go unperceived by the canals, a constant angular acceleration motion will be sensed over a certain period of time in a manner that perception will coincide with the instantaneous angular velocity of the rotation. Equation (13) shows that cupula deviation will be proportional very closely to the instantaneous angular velocity ($\alpha_h t$) for the first 6 to 8 seconds after applying the input acceleration. Whether the CNS is capable to add vectorially signals arriving from the canals when the input acceleration is about an intermediate axis of the canals is still an open question. Qualitative measurements of compensatory eye movements indicate a positive answer; however, subjective perception might differ in this aspect.

The validity of the control model and the use of it has to be viewed in light of the limitations one has to impose due to insufficient experimental support:

1. *Dynamic Range*. Equation (1) shows that for a step input the steady state deviation of the cupula is equal numerically to the input angular acceleration. However, the morphological structure of the semicircular canals and the basic assumption on the cupula sealing the ampulla in its deviated position will probably limit the range of cupular travel within ±30°. Thus a dynamic range of about 100 to 150 for accelerations about the Y_h axis (from 0.2°/sec^2 to 30°/sec^2) and somewhat smaller range for accelerations about the X_h and the Z_h axes are reasonable to expect from these sensors while remaining within their linear characteristics.

2. *Habituation.* The phenomenon has considerable effect on subjective perception of rotation. Also, perceived estimates of angular velocity, but not compensatory eye movements, have been found to decline, contrary to the model prediction, when an input acceleration persisted for periods longer than 30 sec (86). Thus the model is valid for short lasting rotations (about 10 sec) and limited to moderate periods of stimulation which do not cause substantial habituation.

Within the outlined reservations, the control engineering model for the semicircular canals and its associated parameters is a complete set of specifications on those sensors.

4. THE OTOLITHS—LINEAR ACCELERATION SENSORS

The perception of the orientation of the head (and the body) in space, relative to the force fields of the environment, is universally considered to be the function of the otolithic organs. Accordingly, the presence of specific forces acting on the body in its coordinate system is the input to the subjective feeling of orientation provided by these sensors. On a higher level, the otoliths regulate the postural reflexes of the body and the counterrolling compensatory eye movements which preserve the appropriate equilibrium in a given spatial attitude. In all, the otolithic organs are a center of detection and control of the voluntary changes of posture along with monitoring orientation during passive maneuvers of the head and the body as a whole.

However, despite the vital importance of the sensor, little was known about its dynamic characteristics and expected response to specific stimulation. The following discussion will attempt to unify the information scattered in the literature with experimental results obtained by the author into a concise control engineering model of the utricle otoliths.

The Utricle and the Saccule

The anatomical structure of the labyrinth in a human reveals two pairs of otolithic organs, the utricle and the saccule. (See Fig. 2.1.) The structure is characterized by a nonmoving part, the macula, and the sliding otoliths. It is the movement of the heavy otolith over the macula which gives rise to the perceived sensation of tilt or motion.

The specific function of each of the two otolithic organs in motion sensing has been the subject of extensive research effort. In mammalians, physiological studies of reflexes and recording of firing rate from the utricle branch of the vestibular nerve demonstrate activity for stimulation with linear accelerations (1). No similar nerve response to accelerations has been measured from the saccule. A specific study aimed to investigate its activity concludes with the statement that the saccule is probably associated with auditory sensation of vibrations (126). However, some authors still do not exclude the saccule as a motion sensor (130). In general, incorporation of the saccule as an orientation sensor has been required due to the inadequate knowledge of the stimulation process of the utricle. On the basis of the existing experimental evidence, the utricle should be recognized as the only otolithic sensor stimulated by linear accelerations.

The Utricle—Sensor Characteristics

The effort to describe the sensor characteristics of the utricle concentrated on studies of comparative physiology in mammalians, and orientation experiments with humans. In animals, in particular, cats, recordings of nerve firing identified the input vector causing stimulation of the otolith (the term "otolith" will be used here for the "utricle otolith") as tilt away from the vertical (1, 40).

In a fish, electronic microscopy showed an arrangement of sensory hairs with preferred axis of stimulation forming a semicircle (163). This finding might indicate that input vector resolution is possible according to the location of the sensory hair (or hairs) from which nerve firing was received. One can compare this structure of the utricle to a sensor covered with a lattice of strain gages where the input magnitude is obtained by measuring the gage with the maximum output. The spatial location of the strain gage will determine the direction of the input acceleration.

Since subjective perception of inclination with respect to the gravity vector persists as long as this orientation is maintained, the otoliths were designated as static receptors. The implication is, of course, that the utricle is stimulated by changes of the head attitude, thus providing a sense of angular position, while this indication is only transient for the semicircular canals.

The distinction between the gravity field and accelerations in any coordinate system is impossible to make. One can argue here that the utricle is a specific force receptor, where specific force is the vectorial difference of the gravity vector and other intermittent accelerations. Following this broad definition, linear acceleration per se, without restriction on its source, is considered the input variable for the otolithic sensor. Accordingly, exposure to centrifugal or linear acceleration as well as corriolis forces will be interpreted by the human as reorientation with respect to the gravity vector, provided other sensors or sensory systems do not supplement the perceived sensation.

The theory of operation for the utricle and its otolith conceals the key to evaluation of several related characteristics of the sensor. Is the otolith an omnidirectional vector sensor informing on magnitude and direction, or just a directional transducer?

Topologically, for an erect head, the utricles are located on a plane which is elevated about 30° above the horizontal plane. Although the macula and the otolith are not strictly planar, most investigators treat them as such (130, 151). The theories put forth to explain the stimulation causing the otolith displacement range from pull or traction (45), pressure (145), or gliding movement (13).

While de Kleyn supported the notion of force perpendicular to the otolith as the stimulus, Quix explained it by the weight of the otolith, and Breuer implied that the sensor is responding to the direction of the shear force parallel to the macula plane but not to its magnitude. Recently, the shear principle has been rather universally accepted as the mode of operation for the utricle.

Sufficient experimental evidence exists to support the following statements on the otolithic organs:

1. The utricle is a multidirectional sensor sensitive to specific force.
2. The utricle is stimulated by the shear acceleration in the plane of the otolith.

These statements imply that perception of the input variable is in vectorial form; not only the direction of the field force is perceived, but also its strength.

In humans, mostly attempts to evaluate static or steady state conditions of perception of orientation were undertaken. The perceptual phenomenon of tilting surroundings one experiences when subjected to variations of the resultant force in his head axes system has been designated as the oculogravic illusion (11). The phenomenon is a very useful tool to measure subjective orientation (location of the vertical or the horizontal relative to the actual physical inclination). Another experimental procedure uses the human ability to locate the gravity vector when tilted in the frontal plane.

The objective measurements of otoliths output is recording of compensatory counterrolling eye movements (130, 160). Dependence of those eye movements upon the magnitude of resultant acceleration has been demonstrated for increased gravitational and 1.0 g gravity field (173).

Static measurements of the subjective horizon for varying elevation of the head axes system (discrete rotations around Z_e axis) render linear correlation of perception with the shear acceleration on the utricle (151). (See Fig. 4.1.) For an erect head, the shear on the macula is along an axis elevated about 20° above the sagittal axis. Consequently the subjective horizon will correspond to the actual horizon for 0.4 g backward shear acceleration on the otoliths. The measurements confirm the assumption that sensation is dependent upon the magnitude of the shear acceleration, since there is a linear relationship between shear and subjective perception. Experimentally this relationship is valid for ±90° of bending fore and aft. However, incomplete or rather erroneous spatial orientation is suggested by the slope of the line in Figure 4.1. Nevertheless, the sensor is responding to acceleration changes in the sagittal plane in agreement with its assumed characteristics.

Tilt in the frontal plane is associated with perception of the vertical when only gravity is present or perception of the resultant vector for exposure to gravity and linear accelerations. Psychophysical experiments show equal ability for reorientation without directional dependence (123). The observation confirms the expected symmetry of perception in the frontal plane, a feature deduced on the basis of the structure of the

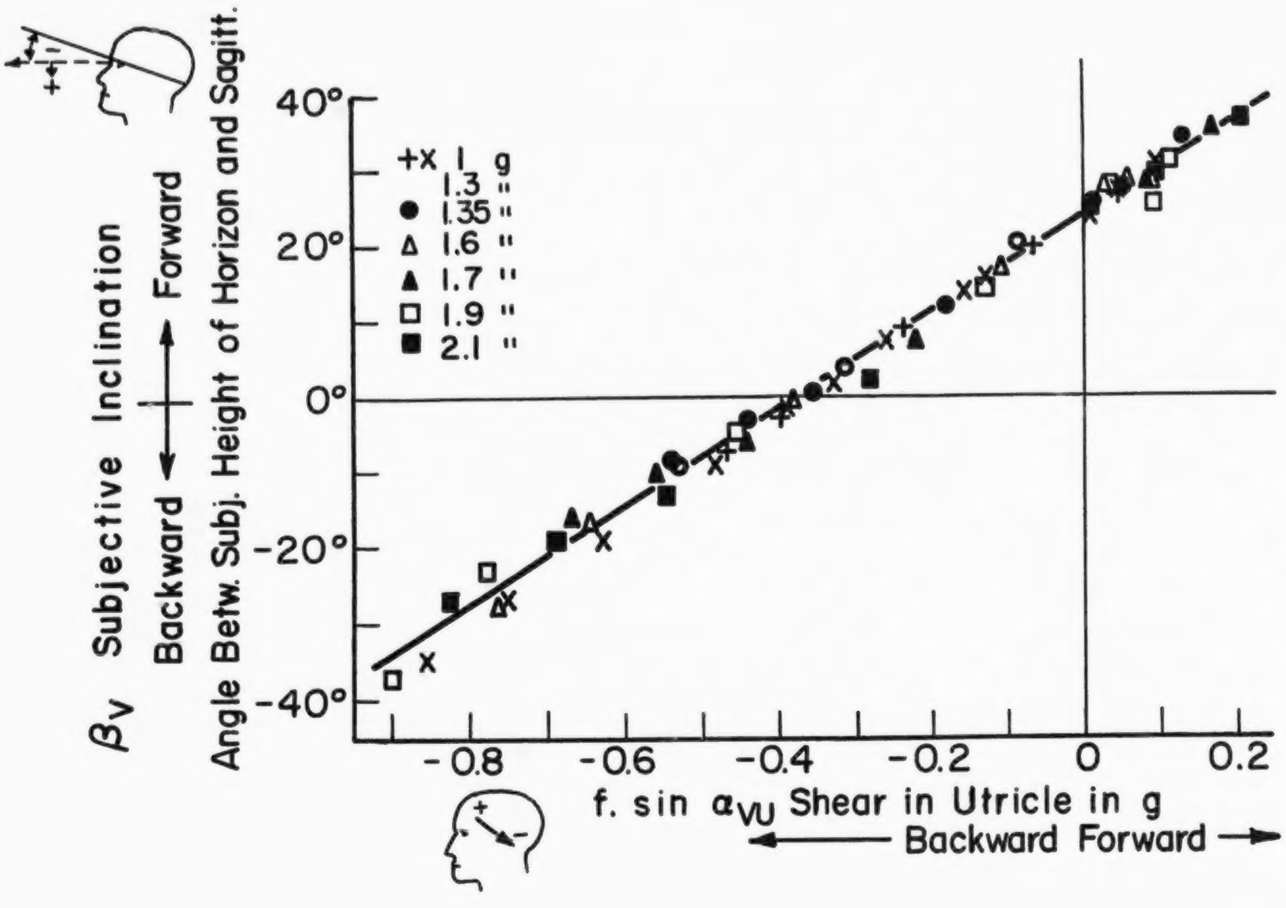


Figure 4.1. The Subjective Inclination (β_V) Plotted As a Function of the Shear Acceleration in the Plane of the Utricle (151)

utricle. Another comment which is valid for the lateral tilt is that the configuration produces shear acceleration components along two perpendicular directions. The resultant shear acceleration on the otoliths very closely obeys a $\cos^2\beta$ relation, where β is the angle of tilt. Counterrolling eye movements which rotate the eye in opposite direction to the body tilt show this relationship very closely (130).

At present, a summary stating that the utricle has sensing capabilities in all directions is well warranted.

Dynamic Response of the Otoliths. The important contribution of the utricle in space orientation is the continuous monitoring of body attitude relative to the environmental forces. However, the extent of orientation information originating at this sensor cannot be fully evaluated without a detailed knowledge of its dynamic characteristics. Intermediate sensations the human will perceive during transfers from one postural orientation to another, or during exposure to intermittent linear accelerations are a function of the sensor's dynamics. Basically, the questions are what physical vector the otolithic organ senses when it is repeatedly stimulated with a certain time varying pattern of acceleration, and what is the frequency response of the otolith?

The theory of control engineering shows that, in a minimum phase linear system, input-output relations are defined, except for a gain constant, by either the phase difference between output and a sinusoidal input or by the ratio of their respective amplitudes. Therefore, the dynamic characteristics of a linear system are fully determined in the transformed frequency domain when its response is tested over a significant range of input frequencies.

The utricle has been identified as a sensor with linear characteristics when linear accelerations, within the range of $\pm 1.0\ g$ of shear acceleration on the otoliths, are applied in the sagittal plane. (See Fig. 4.1.) Consequently an experiment which compares the phase relationship between the subjective perception of velocity and the input velocity or acceleration is admissible for valid testing of the frequency response of the otoliths.

a. Method: A linear motion simulator was used for the experiment. The subject is seated upright with his sagittal axis horizontal and along the direction of motion. His head is supported on a head rest and his body strapped firmly to the chair. The simulator is driven back and forth along the track with a single frequency, sinusoidal function. Perception of the subject is communicated by a displacement of a light, spring-restrained, stick. Following preexperimental instructions, the subject indicates only the direction of motion he undergoes. Position of the simulator along the track and subject indication were continuously recorded on a paper recorder throughout the experiment. Three subjects with previous experience in psychophysical studies were used for this study.

b. Results: The frequency response of the utricle was examined over the range of 0.02 cps to 0.9 cps at discrete increments of 0.01 cps for the low frequencies and steps of 0.1 cps for the high frequency end. The profile of peak acceleration for the experiment is given in Figure 4.2, the decline of it below 0.1 cps being due to the limited length of the track. Since the subjects were instructed to indicate the direction of their movement, their response during one cycle of back and forth oscillation, at any given frequency, resembled a square wave with a "dead zone" of no indication whenever the stimulus fell below the individual threshold of perception. The operator's response is, of course, his subjective perception of velocity. The phase angle this subjective velocity lags or leads the input velocity is presented in Figure 4.3. Intersubject differences in phase angle data were not statistically significant ($P > 0.1$). Thus results from the three subjects were pooled with mean values at each frequency shown in Figure 4.3. One standard deviation of phase angle at any

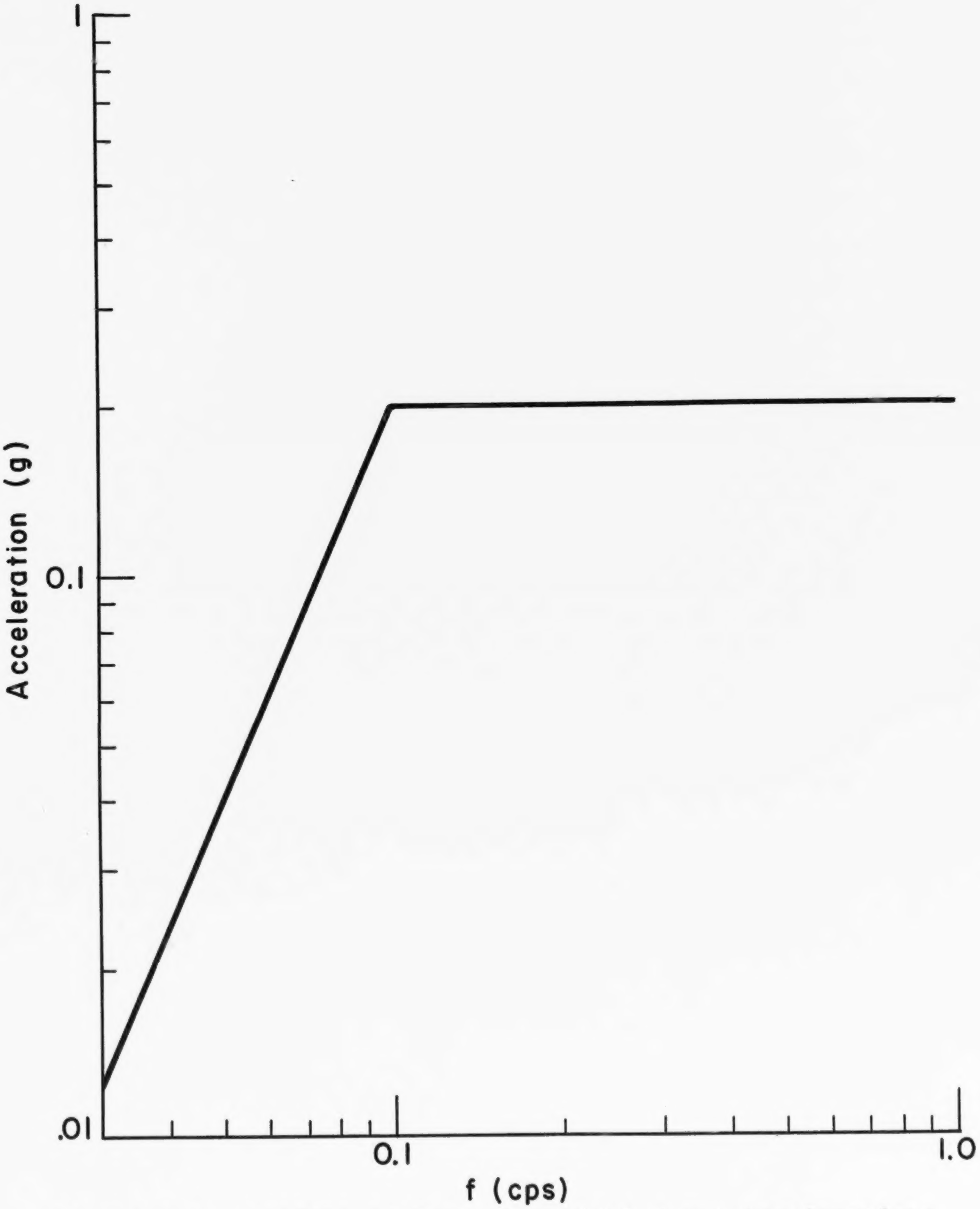


Figure 4.2. Profile of Peak Sinusoidal Input Accelerations

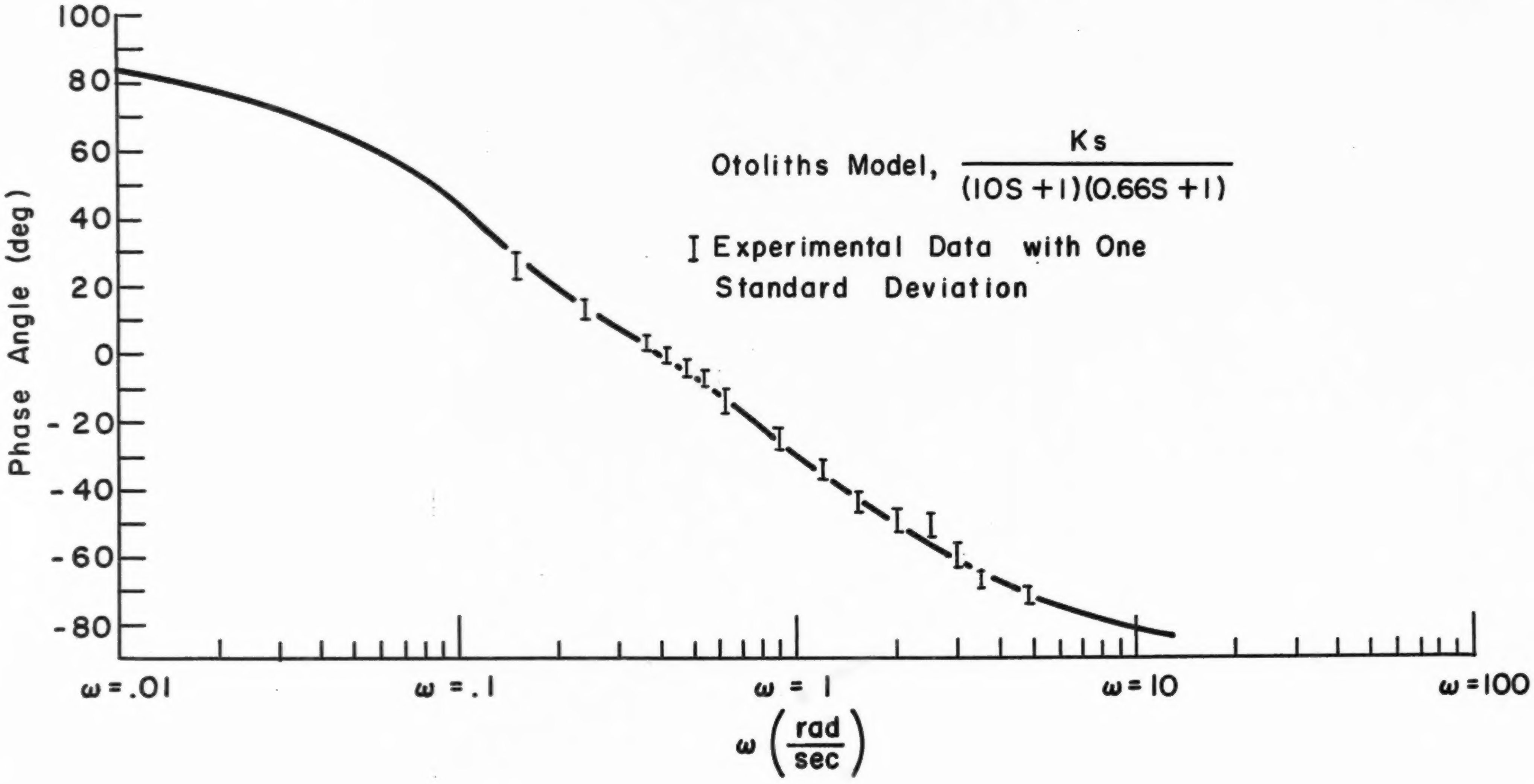


Figure 4.3. Subjective Perception of Motion Reversal--Phase vs Frequency

given frequency did not exceed 2°. Examination of the phase angle for perception of subjective velocity reveals that at low frequencies, it leads the input velocity, at about 0.40 rad/sec it is in phase with it and beyond that frequency, human perception lags behind the input velocity. The response is typical of second order systems with time constants $T_1 = 10$ sec, $T_2 = 0.66$ sec. This theoretical curve fit with break frequencies at $w_1 = 0.1$ rad/sec and $w_2 = 1.5$ rad/sec is the solid curve in Figure 4.3. The phase lag associated with the second order system is in good agreement with the experimental results. In view of this finding, an assumption is made here that the dynamic characteristics of the utricles are represented by a linear second order characteristic equation. The transfer function from input acceleration to subjective sensation of velocity will take the form of

$$\frac{\text{subjective velocity }(s)}{\alpha_{X_e}(s)} = \frac{K}{(10s + 1)(0.66s + 1)} \qquad (15)$$

where α_{X_e} = linear acceleration along the horizontal earth-fixed, X_e axis. The frequency response of the otoliths from an input velocity along the X_e axis to subjective velocity is shown in Figure 4.4. Note that the gain constant K has not been measured.

Threshold of Perception. Threshold of perception for the utricle is significant in terms of minimum deviation in orientation detectable by the sensor. If threshold is associated with minimum displacement of the otolith, the latency time to detect input acceleration of a certain magnitude will correspond to the duration of travel of the otolith from rest position to the threshold deflection. Consequently, the threshold of the utricle is defined as the minimum acceleration which the sensor will detect provided the stimulus persisted for a sufficiently long period. For the otolithic organ, measurements of threshold and latency times in the sagittal plane were undertaken.

a. Method: Again a linear motion simulator was used for these series of experiments. The subject, with strapped body and supported head, was accommodated in two positions: (*1*) seated upright facing the direction of motion; (*2*) lying supine with his longitudinal body axis along the track. The simulator was given a step in acceleration maintained until the subject indicated perception of motion. Directions (backwards or forwards) and magnitudes of acceleration were randomized with the only provision of demanding at least four responses for each input acceleration. Thirty seconds of rest or more were allowed between consecutive runs with the whole series

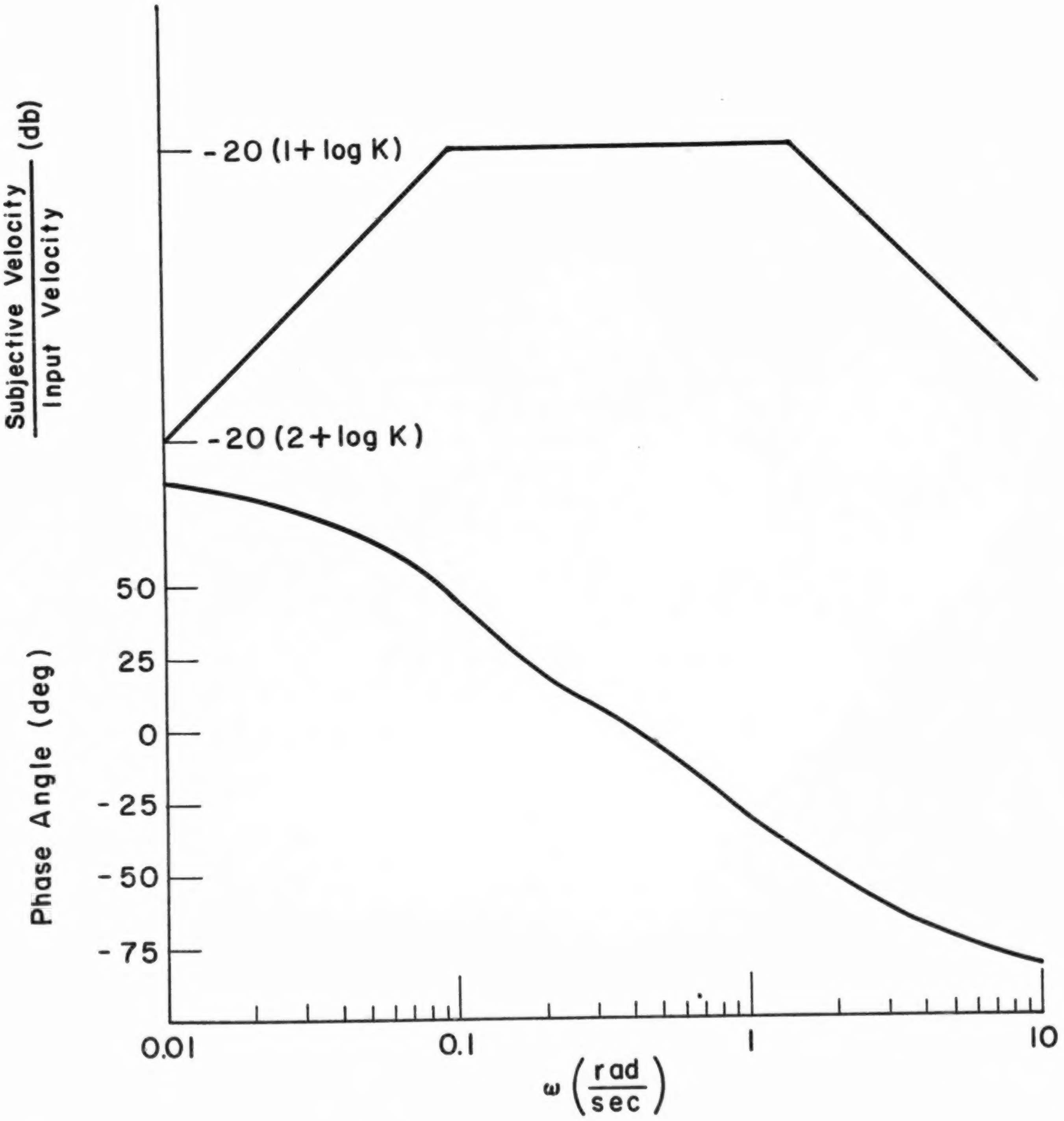


Figure 4.4. Bode Plot of Otoliths Model

lasting for less than one-half hour. The measurements for the upright and the supine position were taken on two consecutive days, while the order changed among the three subjects used in the experiments.

b. Results: The response of the model for the otoliths to a step of acceleration is given by

$$\text{subjective perception } (t) = \alpha_{X_e} K(1 + 0.07e^{-1.5t} - 1.07e^{-0.1t}) \quad (16)$$

If we associate the physical vector of displacement of the otoliths with subjective perception, the threshold will correspond to some minimum travel $d_{\min}$ such that

$$d_{\min} = a_{X_e} K(1 + 0.07e^{-1.5\tau} - 1.07e^{-0.1\tau}) \qquad (17)$$

with a unique relation between the latency times τ measured and the magnitude of the input acceleration, a_{X_e}.

Two immediate observations are apparent from Eq. (16): (*1*) the effect of the term $0.07e^{-1.5\tau}$, drops off almost completely after one second; (*2*) a very slow increase of the factor multiplying the input acceleration during the first second. One can expect then that a wide range of accelerations will be perceived with latency times of about one second.

Figure 4.5 represents the mean latency times of the three subjects for the supine position as a function of input acceleration. The solid line is the theoretical curve from Eq. (17) referred to the experimental measurement at 0.01 *g*. An excellent agreement between experimental results and theoretical prediction, over the whole range covered in the experiment, is noticed. It should be added that the standard deviation for any single time measurement did not exceed 0.2 sec.

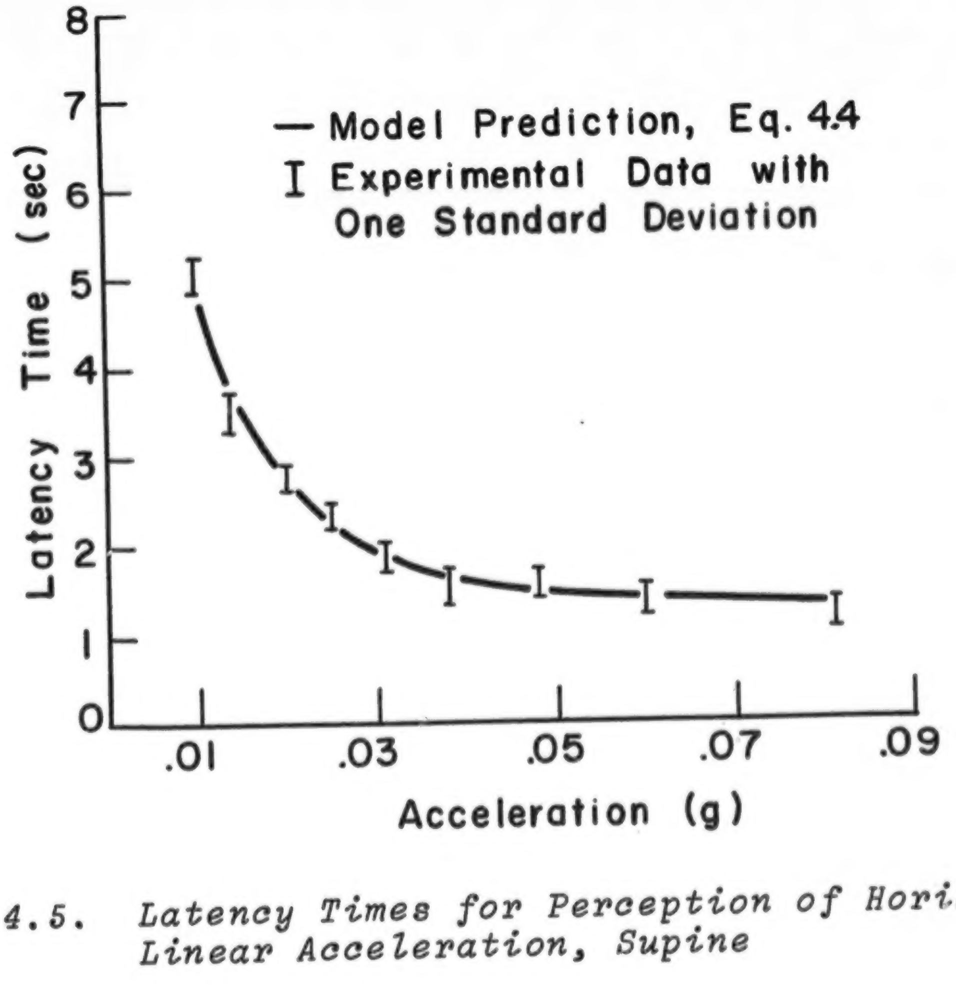


Figure 4.5. Latency Times for Perception of Horizontal Linear Acceleration, Supine

Figure 4.6 shows the experimental latency times for the seated upright position. Note that according to the shear theory there is a difference of shear accelerations between the supine and the upright experimental positions. Since measurements of acceleration along the earth-fixed X_e axis were made, the shear acceleration on the otoliths (assumed 30° elevated above the sagittal axis) is

$$\begin{aligned} 0.866\, ng_e &= a_o \text{ upright} \\ 0.500\, ng_e &= a_o \text{ supine} \end{aligned} \qquad (18)$$

where ng_e = input acceleration along X_e axis and a_o = shear acceleration on the otoliths.

Using these relations and the theoretical, expected latency times for the upright position were computed and are shown as the solid line on Figure 4.6.

The thresholds of perception for the otoliths, based on 75 percent correct vector detection, are 0.01 g for supine head and 0.006 g for upright head.

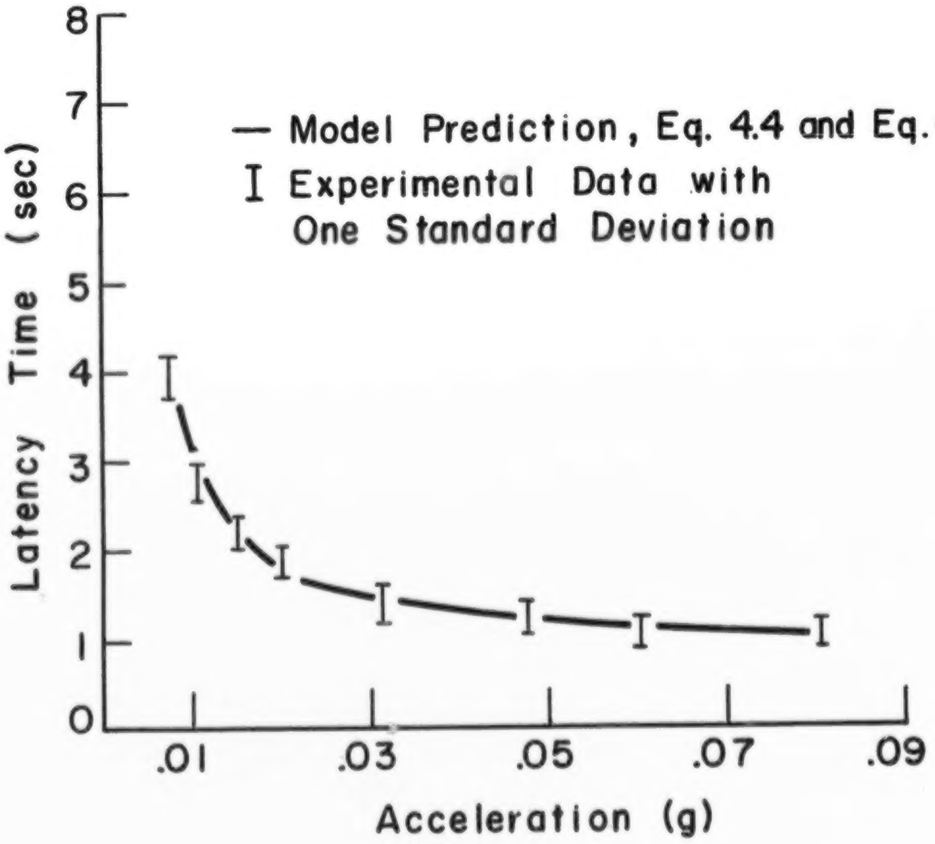


Figure 4.6. Latency Times for Perception of Horizontal Linear Acceleration, Upright

Review of Supporting Publications. The experimental program undertaken by the author was sufficient to determine the dynamic characteristics of the otoliths, and the nonlinearity associated with the threshold. The results are for perception of linear motion along the sagittal axis. Supporting evidence to these findings is found in behavioral experiments reported in the literature.

Researchers working on motion sickness find particular susceptibility to it with linear motion around the frequencies 1/4 to 1/3 cps (109). For the high frequencies, the attenuation in dynamics of the otoliths indeed serve as a limiter on the input accelerations while for frequencies below 1/4 cps; probably equipment limitations on maximum acceleration is the cause for absence of sickness.

The parallel swing produces linear acceleration stimuli, together with some angular acceleration which depends upon the length of the suspending wires. Thus, although the method is not absolutely free of interacting semicircular canals and otoliths stimulation, measurements with it might be of limited use.

The threshold of perception was measured with sinusoidal stimulation on a swing by Walsh (159). For a supine subject, he reports threshold of 0.009 g to 0.012 g. However, an attempt to determine latency times on the swing did not render results which are compatible with other measurements by the same author. Also his attempt to determine phase relations between the subject indication and the actual motion did not render compatible values with this study. This is probably due to the fact that peak accelerations on the swing were very close to the threshold.

The best observation of the function of the otoliths which also illustrates the scope of information the otoliths will provide in an altered environment was made with a submerged subject in a rotating tank full of water (155). The subject seated, was rotated with the tank, head over heels about his z_h axis at constant angular velocity. The force acting on the otoliths is gravity. Therefore, the shear acceleration on the otoliths, for this maneuver, is

$$a_o = g \sin \omega t, \tag{19}$$

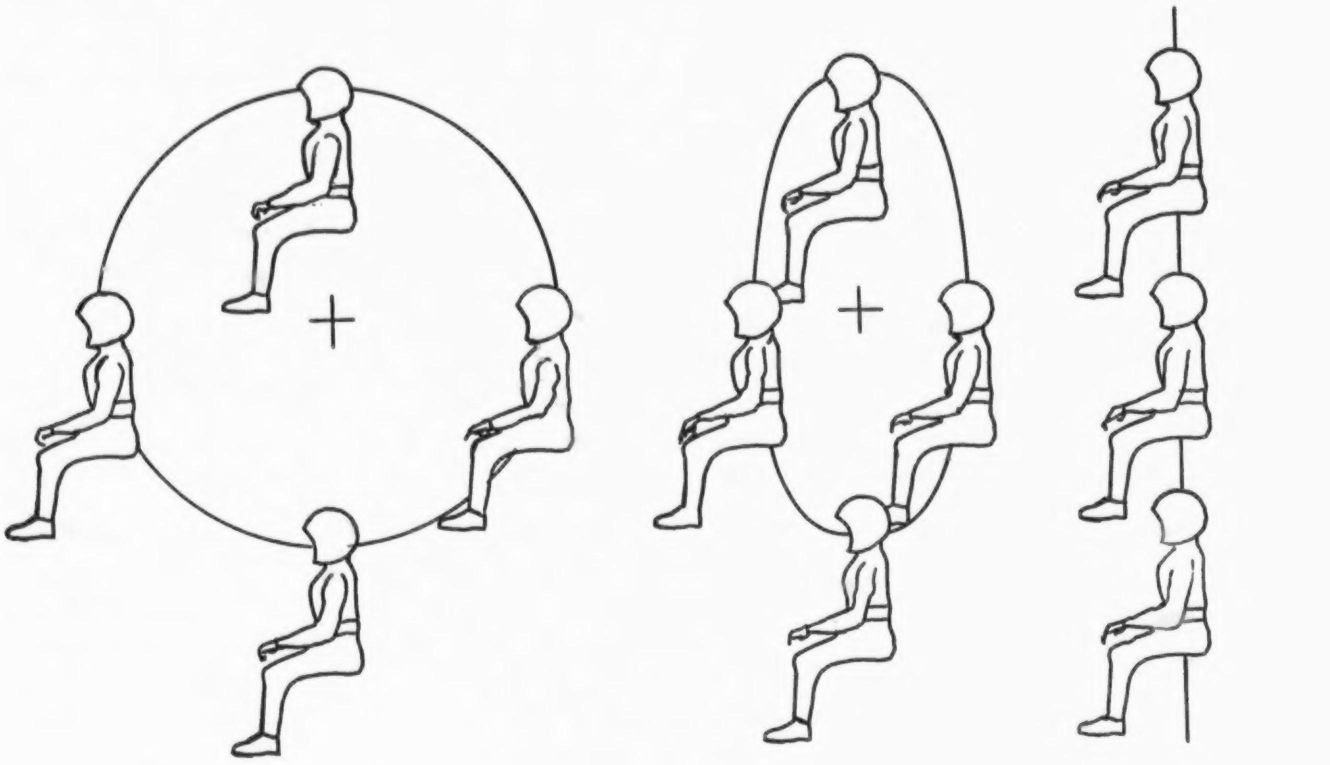
where ω = angular velocity of the tank. The perceived sensation if illustrated in Figure 4.7 taken from Ref. 155. Subjectively, the motion is interpreted as riding a Ferris wheel with varying amplitudes. First, why the Ferris wheel sensation? On a Ferris wheel, which rotates with constant angular velocity, the shear acceleration on the otoliths is combined from gravity and the centrifugal acceleration. Assuming the rider keeps his head erect (otoliths plane about 30° above the horizontal plane), the shear acceleration on the otoliths is

$$a_o = (g + \omega_1{}^2 R \sin \omega_1 t) \sin \frac{\pi}{12}) \qquad (20)$$

where ω_1 = angular velocity of the Ferris wheel and R = radius of the Ferris wheel.

Note that except for an additive constant acceleration (1 g), the shear acceleration for the two cases have similar time patterns. Therefore, in absence of any other motion clues to the undergoing motion (tumbling head over heels), the subject will interpret it in terms of a commonly experienced, similar sensation--the Ferris wheel. It is important to stress the point here that the semicircular canals do not provide rotational information for both circumstances since the motion is with constant angular velocity.

The second observation is about the tendency to feel only plunging, up and down motion with increase in angular velocity. According to the Bode plot for the otoliths, sensation is attenuated with 40 db per decade beyond 1/4 cps. Thus increasing portions of the rotation will pass unnoticed because the shear acceleration dropped below the threshold with the limiting case of only peaks being sensed. Since the maximum forces on the Ferris wheel are indeed at the top and the bottom of the loop, the interpretation forwarded by the subject is consistent with previous experience. Significantly enough, the departure from a circular pattern for the Ferris wheel occurs at 20 rpm (1/3 cps), close to the 1/4 cps break frequency of the otoliths found here.



(a) 0 to 20 rpm. (b) 20 to 55 rpm (c) 55 to 60 rpm

Figure 4.7. Illustration of Motions Sensed by Seated Subject (155)

Habituation

The utricle is often referred to as a statolithic organ, indicating its sensitivity to static changes of orientation of the head with respect to the vertical. In this context, one would expect then little or no attenuation in perception due to frequent stimulation. Otherwise the monitoring capability of the sensor is to no avail. A comparative study of pilots and subjects with no flying experience indeed finds no significant difference between the groups in their ability to orient themselves (10, 11). While long term habituation is excluded logically, it does not inhibit diminution of sensitivity to a new steady state level compatible with the input acceleration. In cats, a shifted otolith will show action potentials at a frequency proportional to the tilt and then the frequency during the following 30 seconds will settle down to a constant value which is about 60 percent of the original (1). Subjective experiments in humans found that readjustments to the gravity vector are significantly more accurate immediately after the tilt compared to readings after 60 seconds of stay in tilted position (123). Moreover, the amount of adaptation in this experiment is of the order of 60 percent of the initial angle of tilt. These findings are supported independently by additional experiments which show the effect of angular rate upon readjustment but almost no influence of the period of exposure to the tilt if longer than 30 sec (57). A summary stating that a short term adaptation of subjective perception takes place during 30 seconds is justified, but the data is not sufficient to put forward a control theory description of it.

Mathematical Model for the Otoliths

The experimental results obtained by the author were from investigations of the otoliths' function in perceiving linear accelerations along the X_e axis. By correlating the data of the upright position with the supine one, it is evident that a unified presentation holds for any head orientation within the range of ±90° rotation of the head frame about the horizontal, earth-fixed axis Z_e. Observations by other researchers indicate the probability of similar response of the otoliths for lateral tilt. Thus one can speculate that the missing link in the control engineering description of the otoliths is the mechanism performing vectorial manipulations and not the dynamics of the sensors. Incidentally, this mechanism of directional resolution will have effect only on the sensitivity of the otoliths. The mathematical model of the otoliths is presented in Figure 4.8. In this model, the specific force in earth-fixed coordinates is resolved to components in the plane of the utricle and perpendicular to it by the orientation matrix and the alignment matrix $[A \times \delta]$. The components along the plane of the otoliths constitute the shear acceleration on

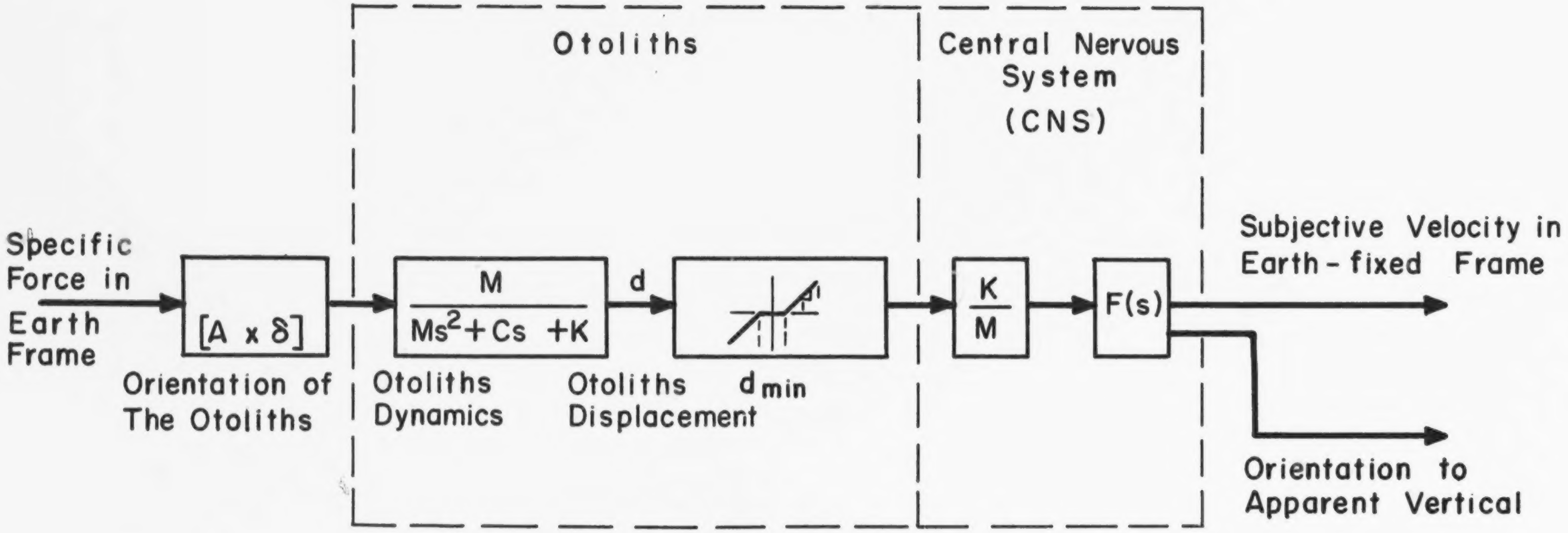

Otoliths
Central Nervous System (CNS)
Specific Force in Earth Frame
[A x δ]
Orientation of The Otoliths
M / Ms²+Cs +K
Otoliths Dynamics
d
Otoliths Displacement
d_min
K / M
F(s)
Subjective Velocity in Earth-fixed Frame
Orientation to Apparent Vertical

Figure 4.8. Otoliths Block Diagram

the otoliths. This acceleration stimulates the otoliths, which after exceeding the threshold, send information to the central nervous system, CNS, where it is interpreted as subjective perception. Some unknown transfer characteristics have to be assigned to the CNS, thus $F(s)$.

The dynamic range of the sensor is not known precisely; however, it is at least 100 or more, since we are living in 1.0 g environment and the threshold has been located as about 0.01 g.

What is the subjective perception attributed to the utricle? Figure 4.4, which is the frequency response of the sensor, presents it as a velocity meter over the spectrum of frequencies corresponding to "normal" head movements. Similarly, the initial (1 to 4 sec) response of the otoliths stimulated by a constant linear acceleration will be proportional to the velocity of the maneuver. The model also indicates that the sensor cannot distinguish between gravity and other acceleration forces. Thus subjective perception of angle of elevation or tilt will be identical regardless of the way it was induced: (*1*) by a change of body orientation with respect to gravity; (*2*) by externally applied accelerations. Figure 4.1 points out that subjective estimates of the angle of elevation are smaller than the actual elevation above the horizon (slope of the line $64°/g$). Since this is steady state data, these readings are probably affected by habituation and reduced to about 60 percent of the initial response. Therefore, for short exposures to tilt from the vertical and to elevation angles above the horizon, the "instantaneous" slope will be about $100°/g$, well correlated with the expected $90°/g$, considering experimental scatter. When time limits are imposed on the duration of exposure to constant acceleration, the adaptation effect, $F(s)$, will not substantially affect the subjective orientation to the apparent vertical.

5. THE EYE—A DEPENDENT SENSOR

The eye perceives body orientation with respect to the environment. This information is of high resolution and is referred to objects observed in the immediate surroundings. In addition, the human can exercise voluntary control of eye movements in searching for a reference to which he relates his orientation. These capabilities of the visual system render the eye as an orientation sensor of prime importance to man. However, the ocular mechanism is by itself a multi-input servo control system with inputs fed to it by other orientation sensors, by the eye itself, and by the voluntary tracking intentions of humans. Therefore, the orientation cues the eye will provide depend upon the visual and motion conditions in the man-environment system, and the dynamic characteristics of the sensors involved in sensing spatial orientation.

Control of Lateral Eye Movements

The eye movement control system rotates the eye in order to maintain the image of an object of fixation upon the retina. A displacement of this image is caused by the motion of the visual target and by rotations of the head on the body. The eye movement control system will respond to these motions with two different modes of eye movements: tracking and compensatory movements. Tracking eye movements follow the moving target in the visual field. Compensatory eye movements rotate the eye in a direction opposite to the rotation of the human body.

The eye has rotational freedom with respect to the skull and the skull as a whole may rotate with respect to the trunk with the neck as a pivot. Accordingly, the eyeball may be considered as mounted on two gimbals with limited freedom of motion with respect to the trunk.

Rotation of the whole gimbal system or relative rotation between the head and the trunk will cause compensatory eye movements. Angular accelerations stimulate the semicircular canals and rotation of the head upon the trunk excites receptors in the neck. Consequently three motion sensors are involved in the eye movement control system: the eye, the semicircular canals and the receptors in the neck.

The schematic diagram in Figure 5.1 shows the multiinput feature of the eye movement control system. The semicircular canals and the relative rotation sensitive, neck receptors are the sensors which provide information about skull motion in space. Since any rotation of the head, if not compensated by an opposite eye movement, will result in image displacement on the retina, the motion information does not need any processing and is fed directly into the motor end of the eye control servomechanism to initiate immediate compensatory eye movements. The tracking movements' branch of the control loop responds to an error between the actual image of a fixation point on the retina and its desired location.

The study of the eye movement control system presented in this section investigates the response of the system in the presence of relative rotation about the vertical axis between the human and the environment. Previously, this control system has been investigated for horizontal eye tracking movements (177). Although compensatory eye movements attributed to the vestibular system are reported in the literature, a detailed frequency response measurement of them has not been presented (96, 135).

The experimental work here is a frequency response study of the eye movement control system for horizontal eye movements. By investigating the separate control loops (except for the visual tracking branch) and their combination, a complete mathematical model of the system is obtained.

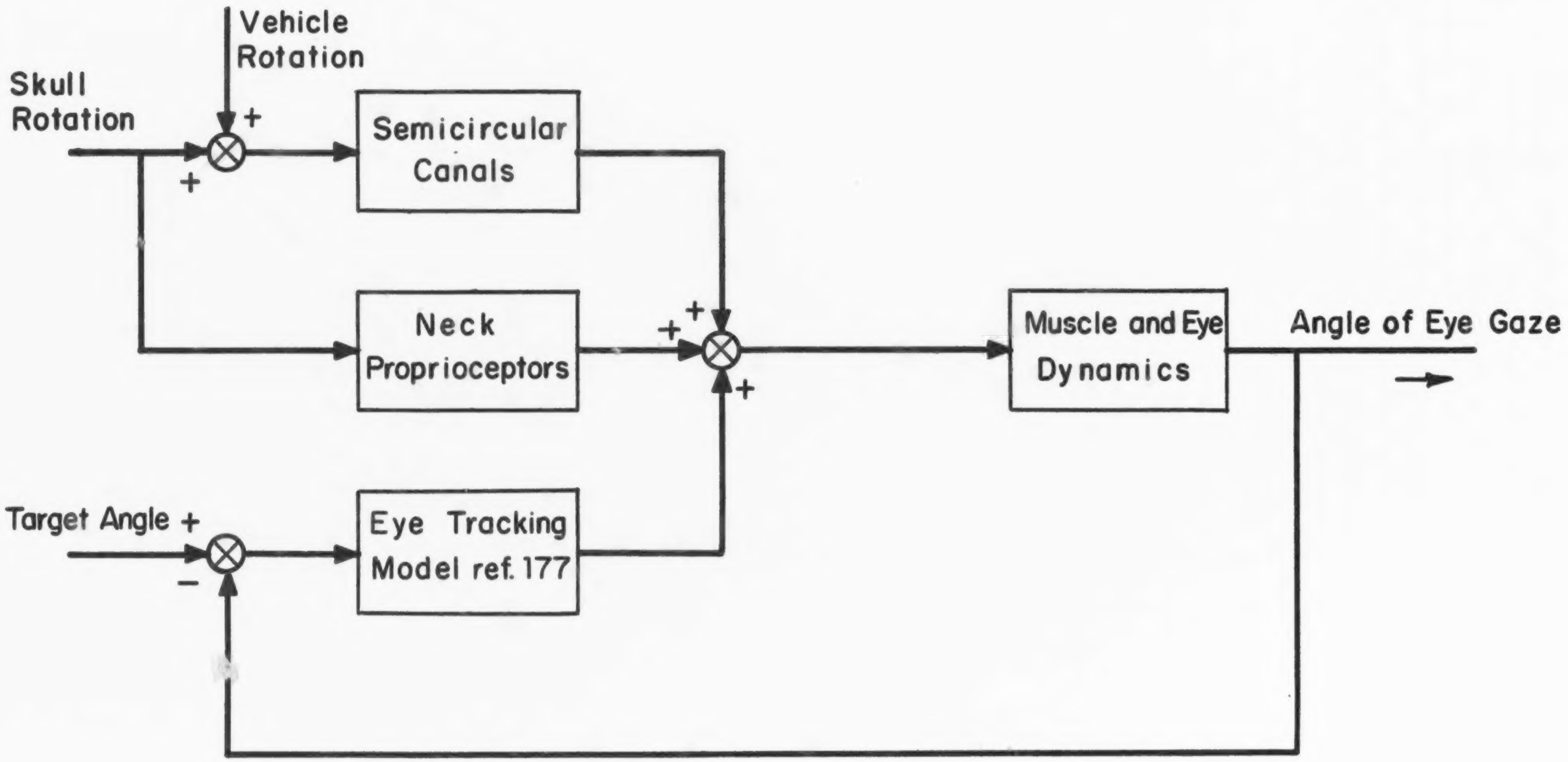

Vehicle Rotation
Skull Rotation
+
+
Semicircular Canals
Neck Proprioceptors
+
+
+
Muscle and Eye Dynamics
Angle of Eye Gaze
Target Angle +
−
Eye Tracking Model ref. 177

Figure 5.1. Block Diagram of the Eye Movement Control System

Rotation of the human body and head can be sensed by the semicircular canals, the neck receptors, or both. The eye movements corresponding to inputs from these sensors are presented as transfer functions from the input vector to the resultant eye motion. The system responses were also investigated when a visual fixation was made to an object both in a rotating and in an earth-fixed environment.

Compensatory Eye Movements—Vestibular Stimulation

The existence of compensatory eye movements accompanying periods of stimulation of the vestibular sensors has been documented extensively (38, 77, 83, 86). As discussed in the third section, compensatory eye movements are considered as an objective measurement of the dynamic response of the semicircular canals. Rotations of the body around a vertical earth-fixed axis do not involve stimulation of the otoliths which exceeds the threshold level. The compensatory eye movements during such rotations and in general are considered to be controlled by the semicircular canals.

The phenomenon of compensatory eye movements maintained by stimulation of the vestibular sensors is known as vestibular nystagmus. This motion of the eye is characterized by a slow rotation opposite to the direction of rotation of the skull called the "slow phase" and fast return in phase with the rotation, the "fast phase." While the slow phase is clearly for image stabilization purposes, the sharp flick of the fast phase has been explained as a return to a new fixation point after a limit of travel off the center position of the eye was reached. However, the nearly uniform time intervals of the fast phase, and the randomness of the angular rotations prior to return suggest control of the central nervous system on it rather than caused by some saturation process (59).

The Cupular Model. The frequency response of the horizontal semicircular canals indicates dynamic characteristics of an angular velocity meter over a range of two decades of frequencies. (See Fig. 3.8.) Thus image stabilization on the retina of the eye during periods of head rotations is possible by control of the eye muscles through the vestibular system. Indeed, fibers from the vestibular nuclei of nerves ascend to reach the motor nuclei of the eye muscles (43, 76). Provided the dynamics of the motor end of the eye are fast enough, the response of the eye to the input from the semicircular canals will resemble the response of the canals to the input rotations. In view of these considerations, the assumption about the velocity of the slow phase of the nystagmus being proportional to the cupula deflection in the canals credits the system design of nature with the best capabilities of image stabilization. According to this assumption, the expected frequency response of the compensatory eye movements, considering the slow phase motion only, can be evaluated as follows:

$$\frac{\theta(s)}{Y_h(s)} = \frac{s^2}{(s + \omega_1)(s + \omega_2)} \qquad (21)$$

where Eq. (21) is the transfer function of the semicircular canals in response to an input angle, , of head rotation. The velocity of the slow phase is assumed to be:

$$sp(s) = -A\ \theta(s) \qquad (22)$$

with p as the cumulative eye position and the minus sign indicating eye movement opposite to the rotation of the skull. A is the sensitivity relating the eye angle, p, to the cupula angle, θ. Consequently,

$$\frac{p^{(s)}}{Y_h^{(s)}} = -\frac{sA}{(s + \omega_1)(s + \omega_2)} \qquad (23)$$

The term cumulative eye position is used to describe the total compensatory travel, relative to the skull, of the eye from a center position. The cumulative eye position is then the sum of all the segments of slow phase motion put end to end by eliminating the effects of several fixation points introduced through flicks of the fast phase.

An experiment to measure the transfer function of the eye movements attributed to stimulation of the semicircular canals [Eq. (23)] was performed by the author. The preferred technique of measurement calls for recording of eye movements of an open eye. In addition, experiments testing the cupular model for compensatory eye movements must keep the subject mentally alert throughout the test period (38).

a. Method: A moving base simulator driven sinusoidally about the earth vertical axis (Y_e) was used as the moving platform for these experimental series. The subject was seated in the hooded cab, his head in the axis of rotation and kept in normal upright position by a biteboard, affixed to the moving cab so as to eliminate any neck movements during rotations. Eye movements relative to the skull were measured by a non-contact method based upon detection of the difference in reflected light from the sclera and the iris on both sides of one eye. A commercial model of an eye movements monitor with a linear range of ±15° and a resolution of 0.1°, mounted on glasses worn by the subject was used for the entire series of experiments described in this chapter. To comply with requirements of complete darkness in the cab (elimination of visual fixation point), the necessary illumination of the eye ball was achieved by an infrared light. Recording of the cab position and eye movements were taken continuously during the experiments. Three subjects participated in the experimental series discussed in this section.

b. Results and Discussion: The profile of frequencies and corresponding amplitudes of the input rotation are given in Figure 5.2. This profile in effect kept the peak angular accelerations constant for high frequencies. Figure 5.3 is a recording taken for $f = 0.5$ cps. The upper trace is the vestibular nystagmus measured relative to the skull, cumulative eye position is shown in the middle, and the lower trace is the input position of the cab. Note the clear sinusoidal shape exhibited by the cumulative eye position. With sufficient care exercised, this method of analysis rendered sinusoidal input-output relations for the whole spectrum of input frequencies (0.03 cps-2.0 cps). Therefore, adequate information on the transfer function from input angular velocity to the compensatory eye velocity in terms of amplitude ratio and phase angle was obtained. This data is summarized in Figure 5.4 which presents the experimental results along with a minimum phase transfer function fit to them. This relationship is given by

$$\frac{\text{eye velocity }(s)}{\text{input angular velocity }(s)} = \frac{-\,3.2s}{(8s + 1)(0.04s + 1)} \tag{24}$$

It is found that the break frequencies of the cupular model for objective measurement are displaced with respect to evaluation based on subjective perception. However, the important finding is concerned with the gain of the transfer function, or the ratio between the compensatory eye velocity and the skull velocity. This factor determines the extent of image stabilization upon the eye which can be achieved by the vestibular system, while angular accelerations are applied on the body as a whole. In contrast to a common presentation which assumes temporal (between two consecutive fast phase movements) preservation of a stationary picture by the eye, the compensation measured in these series of experiments is only fractional. Over a wide range of input frequencies (see Fig 5.4) the eye compensatory velocity is about 40 percent of the angular velocity of the skull with respect to the environment. Two other publications support this finding: the initial eye velocity responding to a step of angular velocity was found to be (*1*) 43 percent of the stimulus (102); (*2*) 45 percent of the stimulus (101).

The significance of the results presented here is far reaching. Since the angular velocity of the skull is not completely matched by the relative velocity of the eye with respect to the skull, the image upon the retina is not stationary but moves in the direction of rotation. Accordingly, one has to conclude that the vestibular system alone, or more specifically, the semicircular canals cannot achieve space stabilization of the eye when the skull, together with the body, undergoes passive rotations.

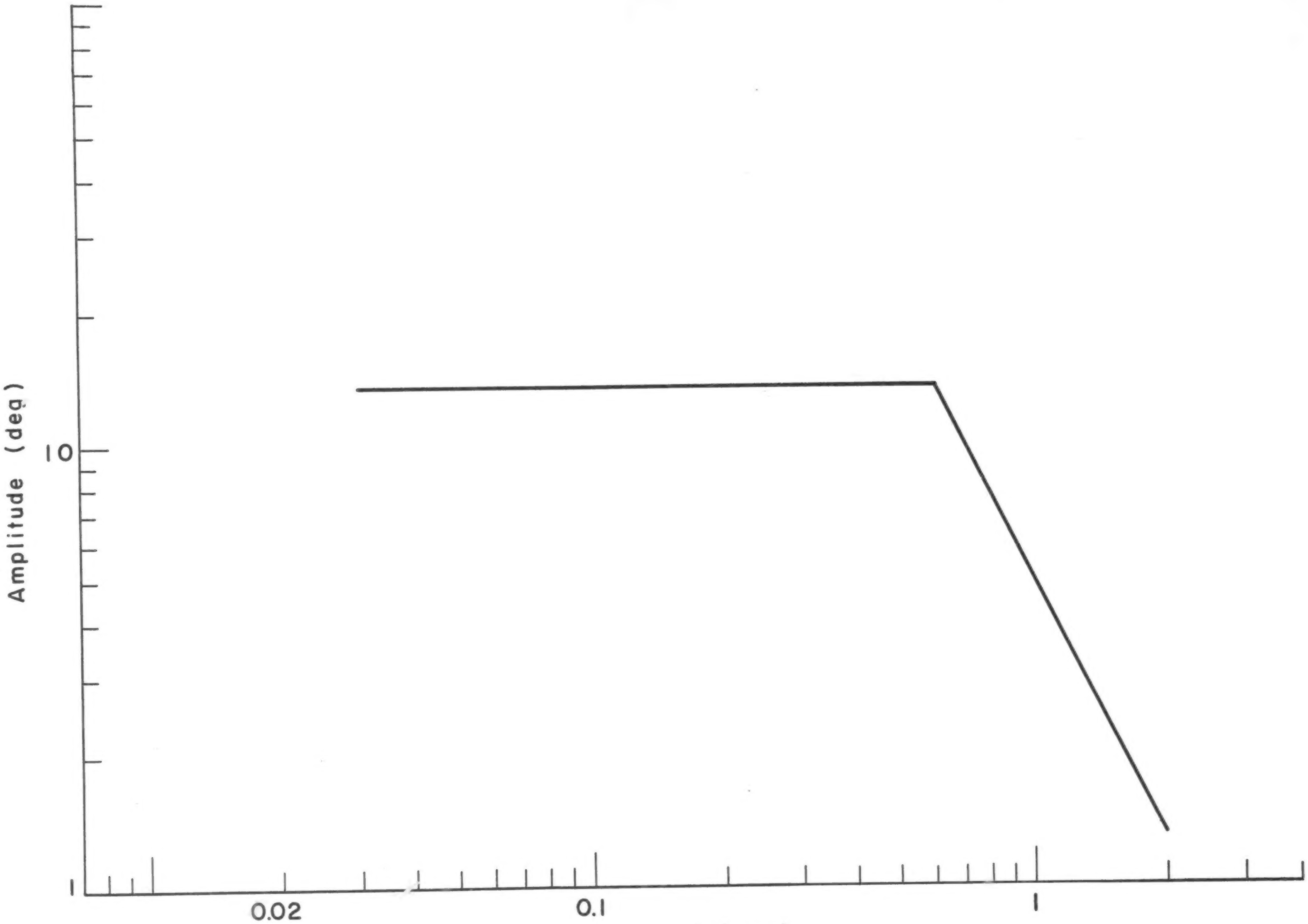


Figure 5.2. Profile of Input Sinusoid Amplitudes

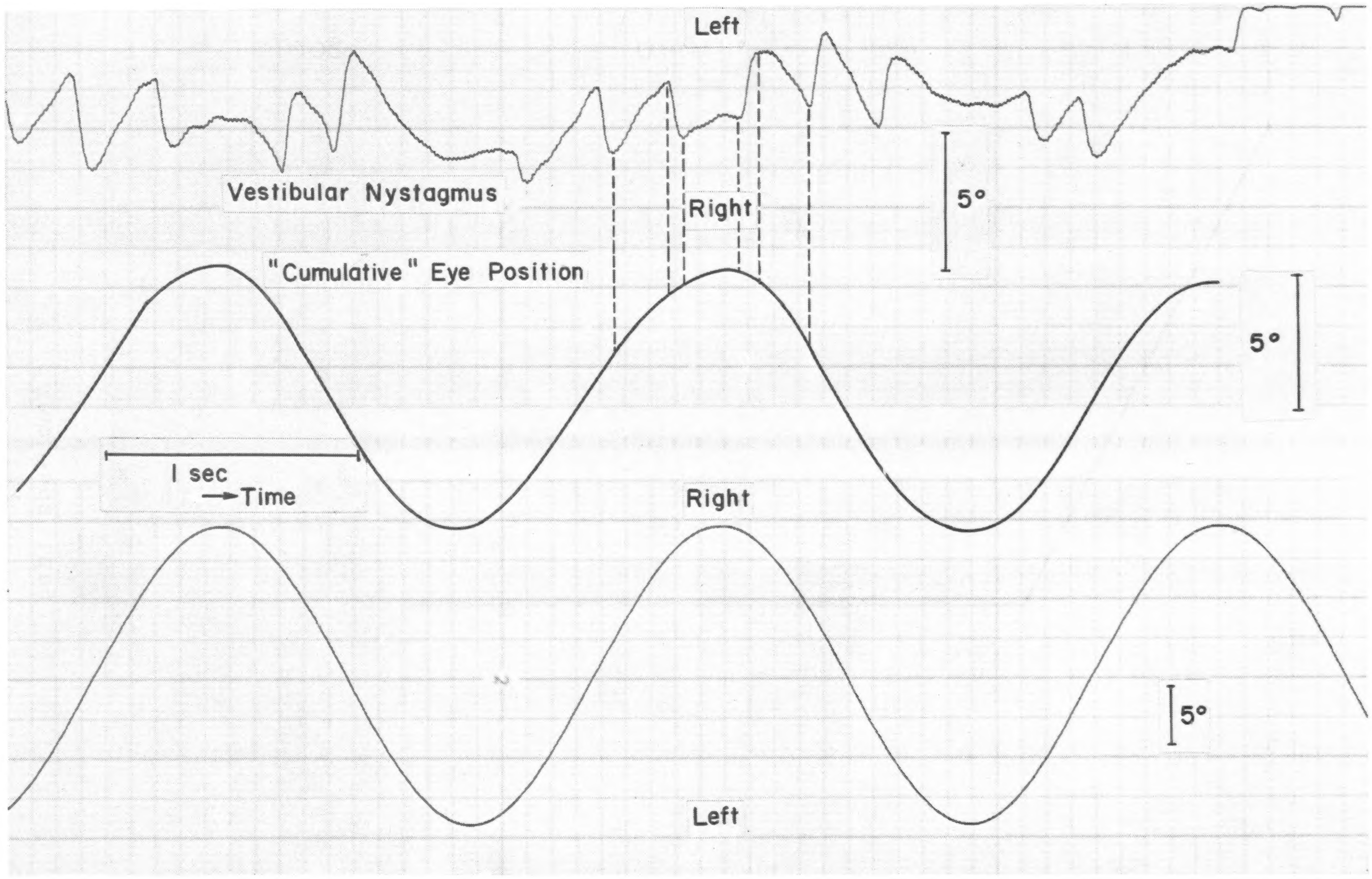


Figure 5.3. Vestibular Nystagmus and "Cumulative" Eye Position, f = *0.5 cps*

(Note the correspondence of slow phase vestibular nystagmus and "cumulative" eye position.)

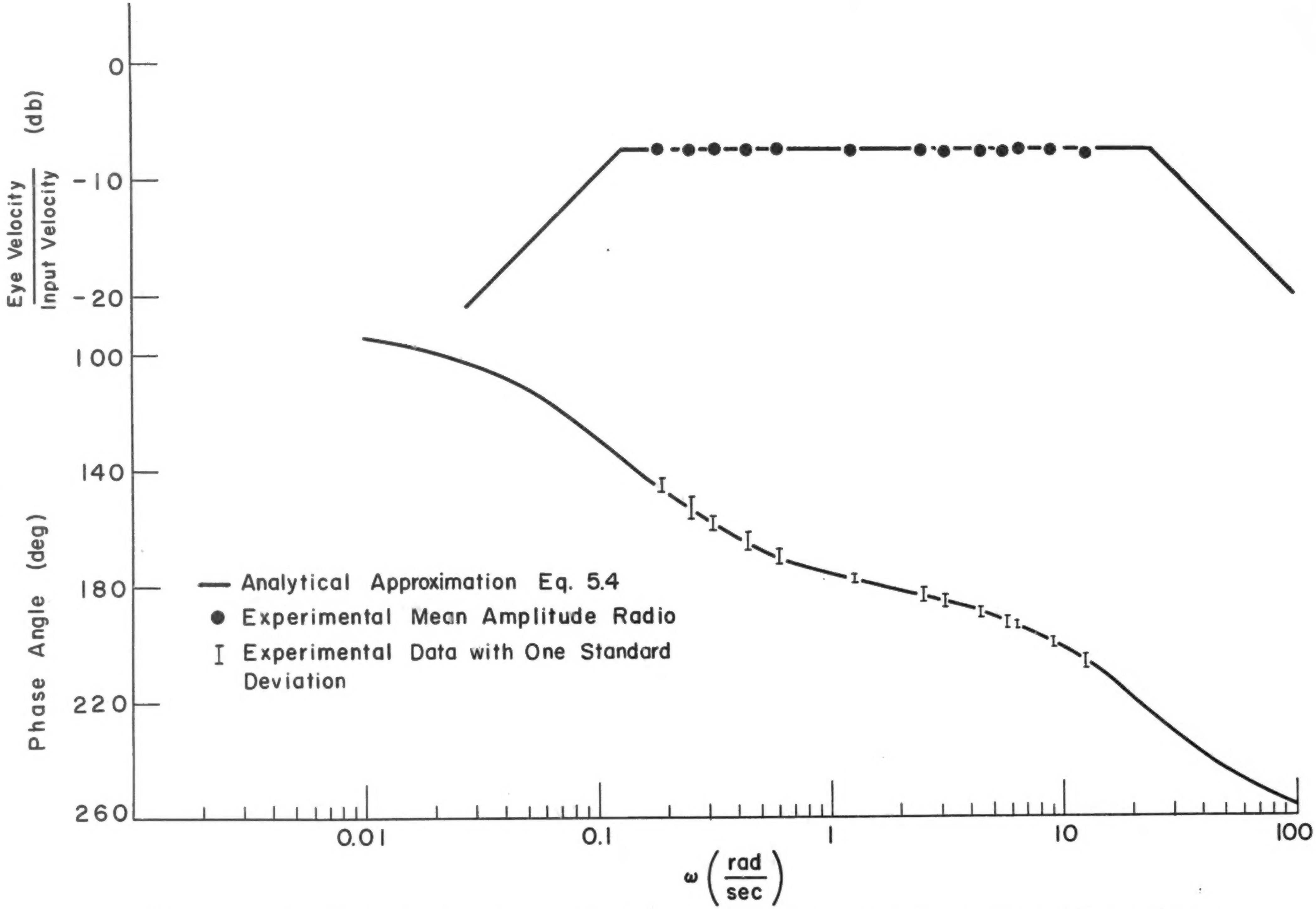


Figure 5.4. Bode Plot of Vestibular Compensatory Eye Movements (Slow Phase)

Environmental Fixation. The block diagram in Figure 5.1 shows that the vestibular branch and the tracking path of the eye movement control system are activated when the subject is rotated and the eye has a visible fixation point. If the fixation point rotates with the subject, this is an environmental fixation. The situation corresponds to the common condition of travel in a maneuvering vehicle whose interior is fully illuminated and the view of the external world is obscured. The fixation point is stationary with respect to the traveler. However, its image upon the retina will move due to the compensatory eye movements initiated by the stimulated semicircular canals. The expected eye movements will exhibit a saw tooth pattern, where the eye is deviated from its mean position by the vestibular branch and returned to it by visual tracking.

Experimentally, the proper environment was simulated by illuminating the inside of the cab of the moving base simulator. Otherwise, the experimental conditions were maintained as previously, with the subjects instructed to maintain fixation upon a crossed marker mounted in the cab at eye level and four feet away.

Figure 5.5 is a record taken at $f = 0.5$ cps. On the upper trace, one can distinguish the nystagmic beats changing from left to right every cycle. Note that by voluntary fixation the control system maintains the mean eye position fixed with respect to the skull. Consequently, the image of the rotating environment is kept approximately stationary on the retina. For the spectrum of frequencies examined in this series, the eye remained within ±0.5° of its mean position.

Earth-fixed Fixation Point. If an object in the nonmoving surroundings is fixated upon, the control system of the eye will maintain its image on the retina, provided the limits of angular travel of the eye were not exceeded. Physically, the description applies to a human in a rotating vehicle and attempting to look at a given spot outside it. The vestibular compensatory eye movements and the tracking path of the control system are in phase for these conditions. Therefore they are combining to keep the fixation point image stationary.

Experimentally, by removing the hood from the cab of the moving base simulator and illuminating the surroundings, a duplication of the described conditions was achieved. A crossed marker was taped to the wall of the room 8 ft away from the subject and at his eye level. The subject was instructed to maintain fixation upon the marker throughout the experiment.

A record taken at $f = 1.0$ cps is shown in Figure 5.6. Note the regularity of the eye position, tracing a perfect sinusoid, a feature observed for all the frequency range

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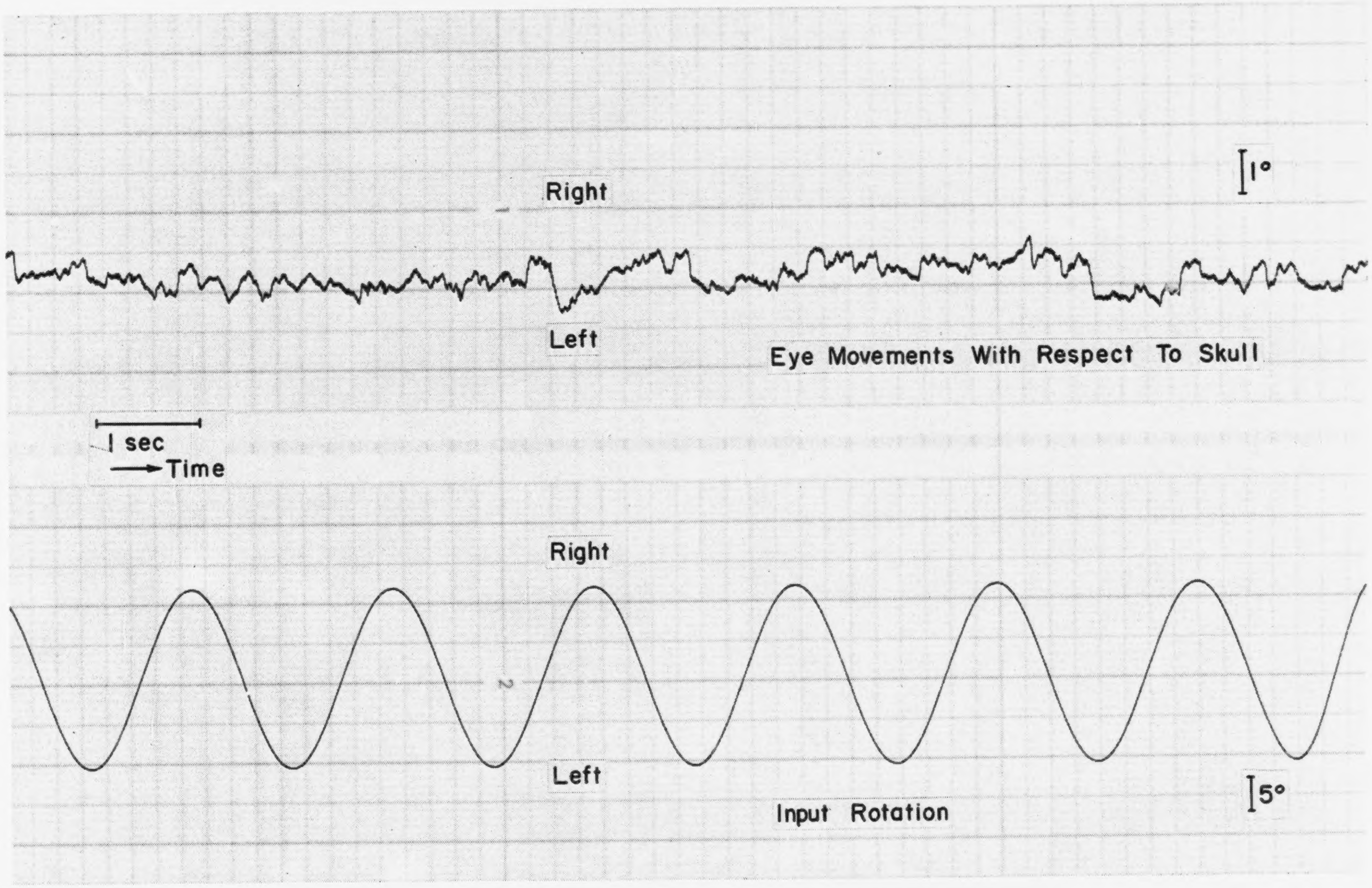

Figure 5.5. Vestibular Nystagmus with Environmental Fixation Point, f = 0.5 cps

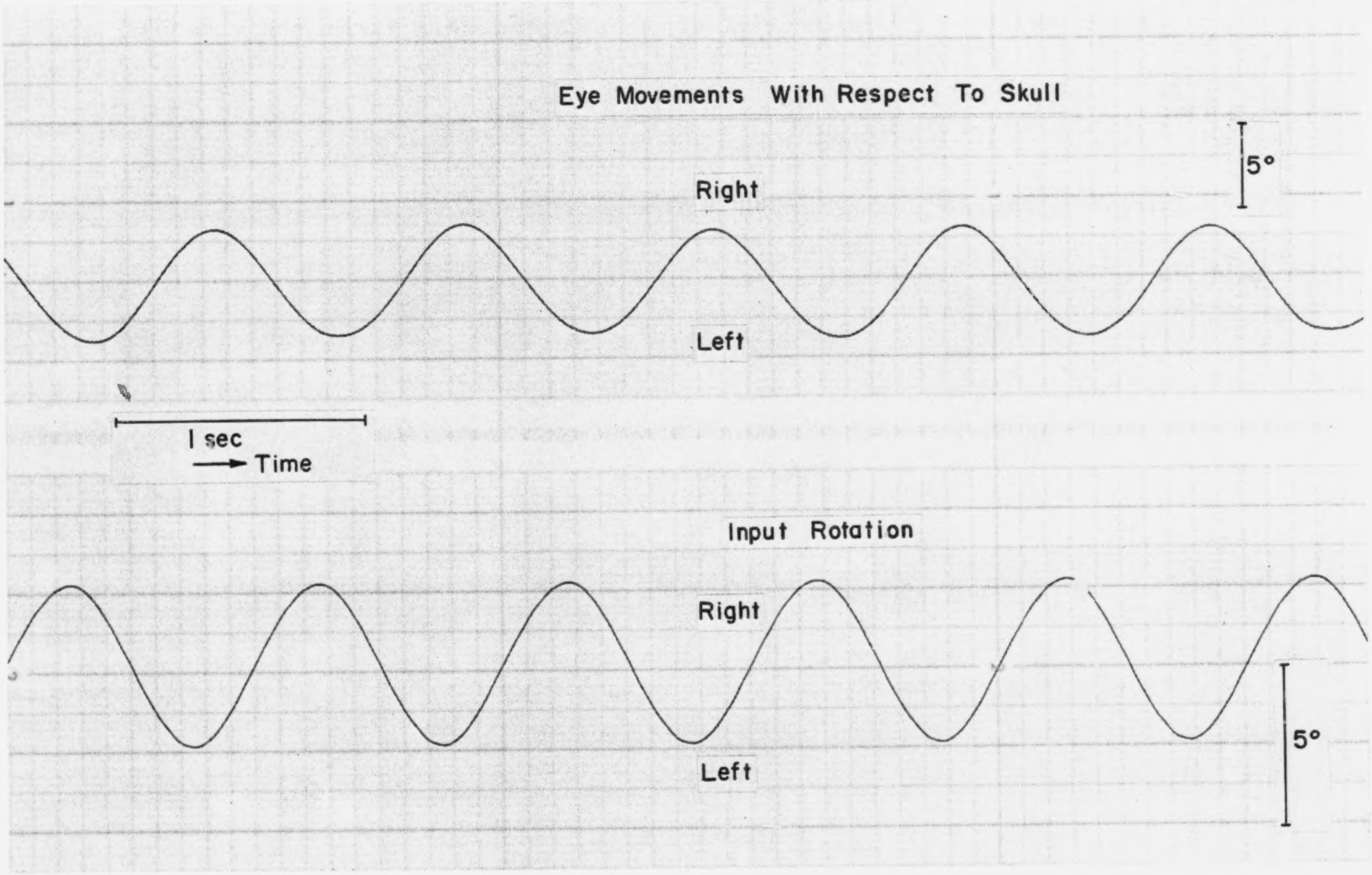

Figure 5.6. Vestibular Compensatory Eye Movements with Earth-fixed Fixation Point, f = 1.0 cps

(0.03 cps to 2.0 cps) of the experiment. The frequency response of the eye movement control system with earth-fixed fixation point is presented in Figure 5.7. Perfect compensation of amplitude is achieved over the range of two decades of frequencies approximately, with the phase lag, however, increasing rapidly beyond 0.5 cps. These results point out the capacity of the control mechanism to maintain a stationary reference for the visual system in presence of disturbances in the form of vehicle rotations. The observation holds as long as the limit of rotation of the eye has not been exceeded during the rotational maneuver.

Compensatory Eye Movements—Neck Proprioceptors

The role of neck receptors as a source of compensatory eye movements has been suggested by physiologists in early literature (54). In the rabbit, eye movements were recorded while the neck was bent, but the validity of the observation is questionable since the vestibular system of the animal was also stimulated in the process. For man, the only experiment intended to isolate the effect of neck receptors upon eye movements is reported in the literature back in 1928. The conclusion the author reached there maintains that for the experimental condition of fixed head and moving trunk, the corresponding eye movements were small (54).

If compensatory eye movements are produced, the atlanto-axial joints of the neck and the muscles participating in the relative head-trunk rotation (see Appendix C) have to contain the nerve endings which control the oculomotor muscles. Unlike the nerves of the vestibular system, no direct pathway from the nerves of the neck joints and muscles to the motor nuclei of the eye has been identified yet (43). Nevertheless, through central processing or a feedback path to the vestibular nerves, a tie pathway of innervation from the neck receptors to the eye muscles is, in all probability, established.

The experimental setup for the vestibular stimulation was rearranged to allow rotation of the trunk while the head is kept still. The subject was seated in the cab of the simulator with the vertical axis of it running along the neck. His eye was illuminated with a stationary infrared light source. With the skull fixed to the stationary gimbal of the simulator by a bite board, care was exercised to provide rotation of the trunk that is free of bending.

As seen in Figure 5.8, distinct compensatory eye movements are recorded for sinusoidal rotation of the trunk. The experimental record is for input frequency of 0.6 cps and the input amplitude is ±13.5 degs. The "cumulative" eye position shows an angular travel of the eyeball of ±1.0 degs.

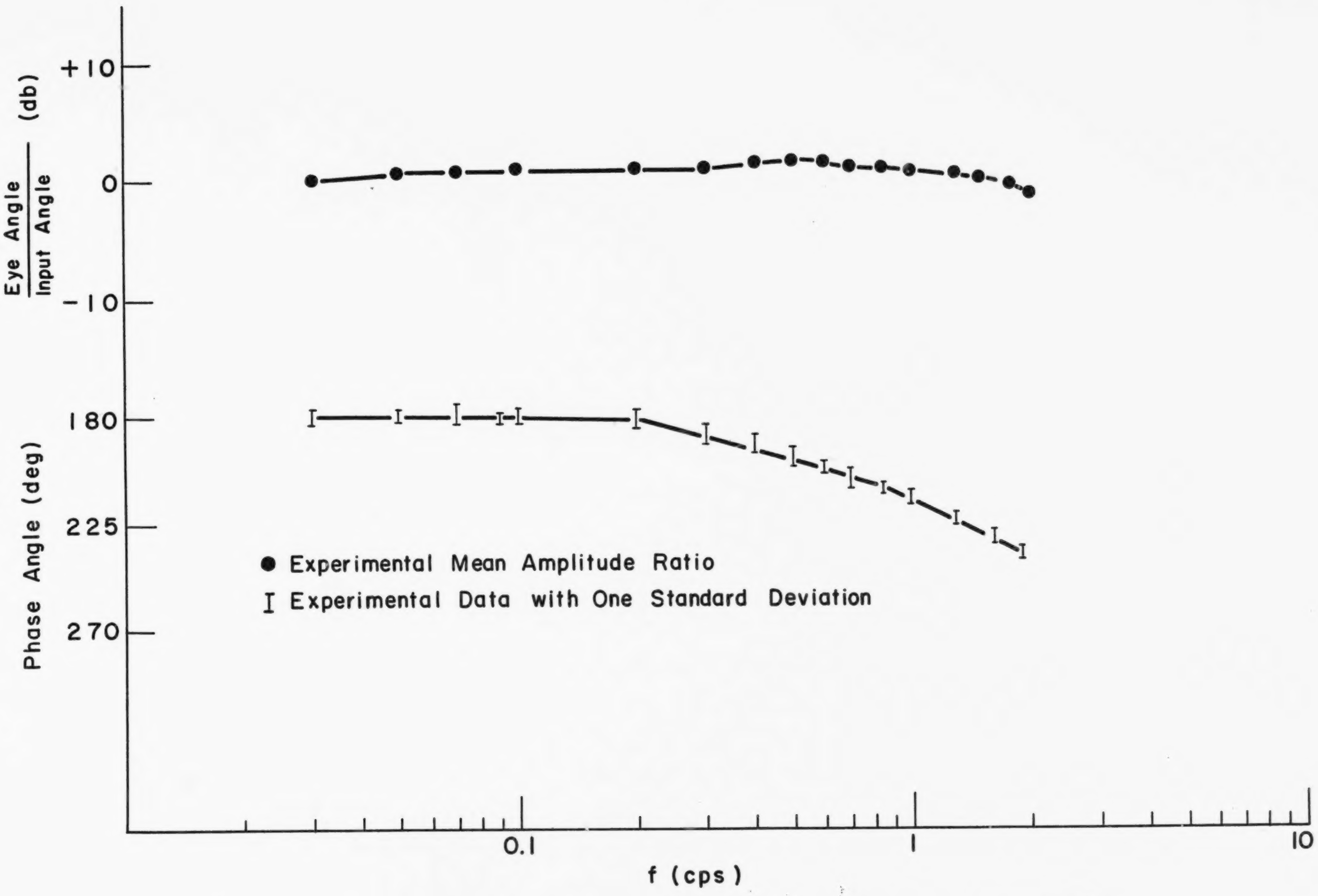

Figure 5.7. Bode Plot of Compensatory Eye Movements (Vestibular Stimulation with Earth Fixation Point)

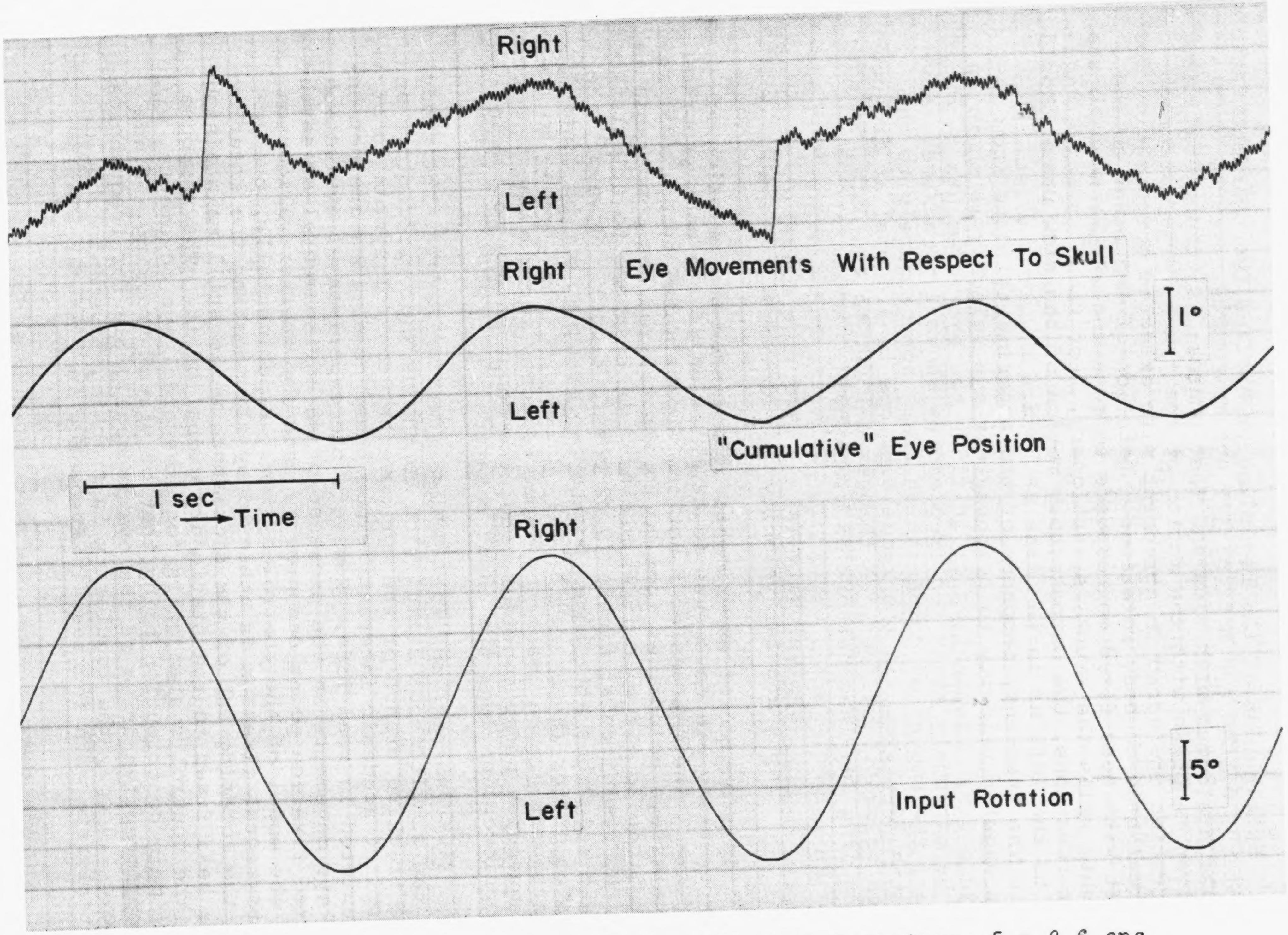

Figure 5.8. *Compensatory Eye Movements by Neck Receptors, f = 0.6 cps*

Examination of the recording emphasizes two characteristic features of the eye motion: (*1*) eye movements resemble vestibular nystagmus with slow and fast phases; (*2*) the eyeball is driven in phase with the motion of the trunk. The latter observation is indeed in agreement with expected compensation for normal head on body rotations. Rotation of the trunk to the left with head fixed corresponds to rotation of the head to the right, while the trunk is stationary. For these relative angular rotations, the compensatory motion of the slow phase should be to the left as is the case at hand.

The frequency response of the experimental data from input angular velocity to compensatory eye velocity is shown in Figure 5.9. Examination of it finds the eye movements recorded to be extremely small for frequencies above 2.5 rad/sec. However, the amount of compensation rises approximately to the vestibular level (in the range 0.02 cps to 4.0 cps) at frequencies below 0.6 rad/sec. A theoretical fit to the data, in the form of a lag-lead network is given by:

$$\frac{\text{eye velocity } (s)}{\text{input angular velocity}} = \frac{.325\ (1 + 0.43s)}{(1 + 1.74s)} \qquad (25)$$

This series of experiments established the relation of compensatory eye movements to stimulation of the neck proprioceptors. Their transfer function, approximated by Eq. (25) indicates eye velocities from DC to about 1 rad/sec comparable in amplitude to the velocities measured in response to stimulation of the semicircular canals (0.02 cps to 4 cps). However, the phase relations attributed to the two branches of the control system differ rather radically. While eye velocity due to the vestibular branch leads the input velocity for the spectrum of frequencies under consideration, the compensatory motion by proprioception lags the input rotation.

Environmental and Earth-fixed Fixation Points. The study of the simultaneous stimulation to the neck proprioceptors and the tracking branch of the eye movement control system is of a distinct academic interest, since these conditions are not encountered in real life. However, the experimental evaluation of eye movements in the presence of an environmental or earth-fixed fixation point can provide data for further validation of the model of the control system. Experimentally, the environmental fixation is achieved by illuminating the interior of the rotating cab of the simulator, while still maintaining the head fixed to the stationary gimbal of it. The response of the control system calls for sinusoidal eye movements, with the main contribution being that of visual tracking. Since proprioceptive drive of the eye is negligible for frequencies above 4.0 cps, the regularity in tracking movements should deteriorate with increase in frequency in a manner similar

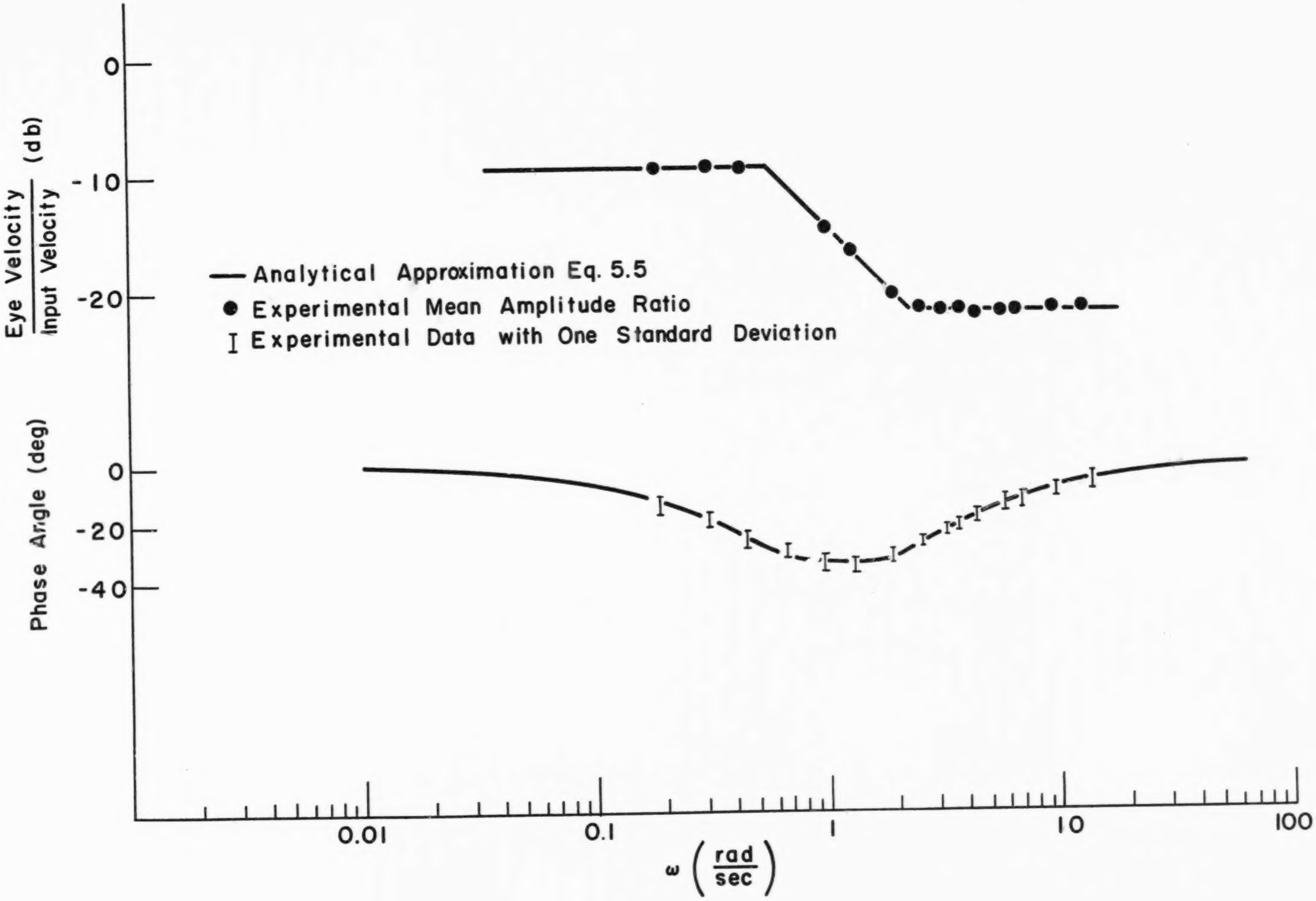

Figure 5.9. Bode Plot of Compensatory Eye Movements by Neck Proprioception

to the movements recorded for tracking only (177). The record shown in Figure 5.10 is for eye movements with environmental fixation at f = 0.8 cps. When the input frequency is raised further, the Fourier series of the response contain sizable terms besides the fundamental.

With earth-fixed fixation point during stimulation of the neck receptors, the eye is driven to maintain its mean position constant relative to the skull. Therefore, at low frequencies, the visual tracking loop should correct for compensatory movements driven by the proprioceptors, and at high frequencies the tracking loop prevents eye drift. Examination of Figure 5.11, which presents movements with earth-fixed fixation point at f = 0.2 cps, supports this notion of response of the eye movement control system. The total travel of the eye from its center position is ±0.5 degs, while the "cumulative" eye position for the same conditions without a fixation should have been ±2.0 degs.

Compensatory Eye Movements—Vestibular and Neck Proprioceptors Stimulation

Frequent movements of the human involve rotation of the head while the eye is fixated upon a given object in the visual field. During these rotating motions, the vestibular system and the neck proprioceptors are stimulated. Therefore, the accompanying eye movements are due to all three of the motion sensors, the eye, the semicircular canals and the neck proprioceptors. The compensation achieved for these circumstances is a measure of the maximum capability of the eye movement control system to preserve a stationary reference on the eye.

One should raise the question whether the control system is linear over the spectrum of frequencies measured in these series of experiments. If affirmative, the compensatory eye movements for combined stimulation of the three motion sensors will be the vectorial sum of the individual contributions by the semicircular canals, the neck proprioceptors, and visual tracking. The importance of the concept of linearity of the control system is far reaching. By virtue of it, compensatory eye movements are predictable just on the basis of the data on the environmental conditions and a mathematical model of the control system. Evidently, the crucial experiment testing the linearity of the system is for combined stimulation of the semicircular canals and the neck proprioceptors in the absence of visual fixation.

a. Method: The subject was accommodated in a chair with his back supported in upright position. His head was fitted with an adjustable head band which carried a small infrared light. A potentiometer with its case stationary and its slider in the head band was used to measure head position. The experimenter, by counting throughout the experiment, provided the beat according to which the subject rotated his head, simulating

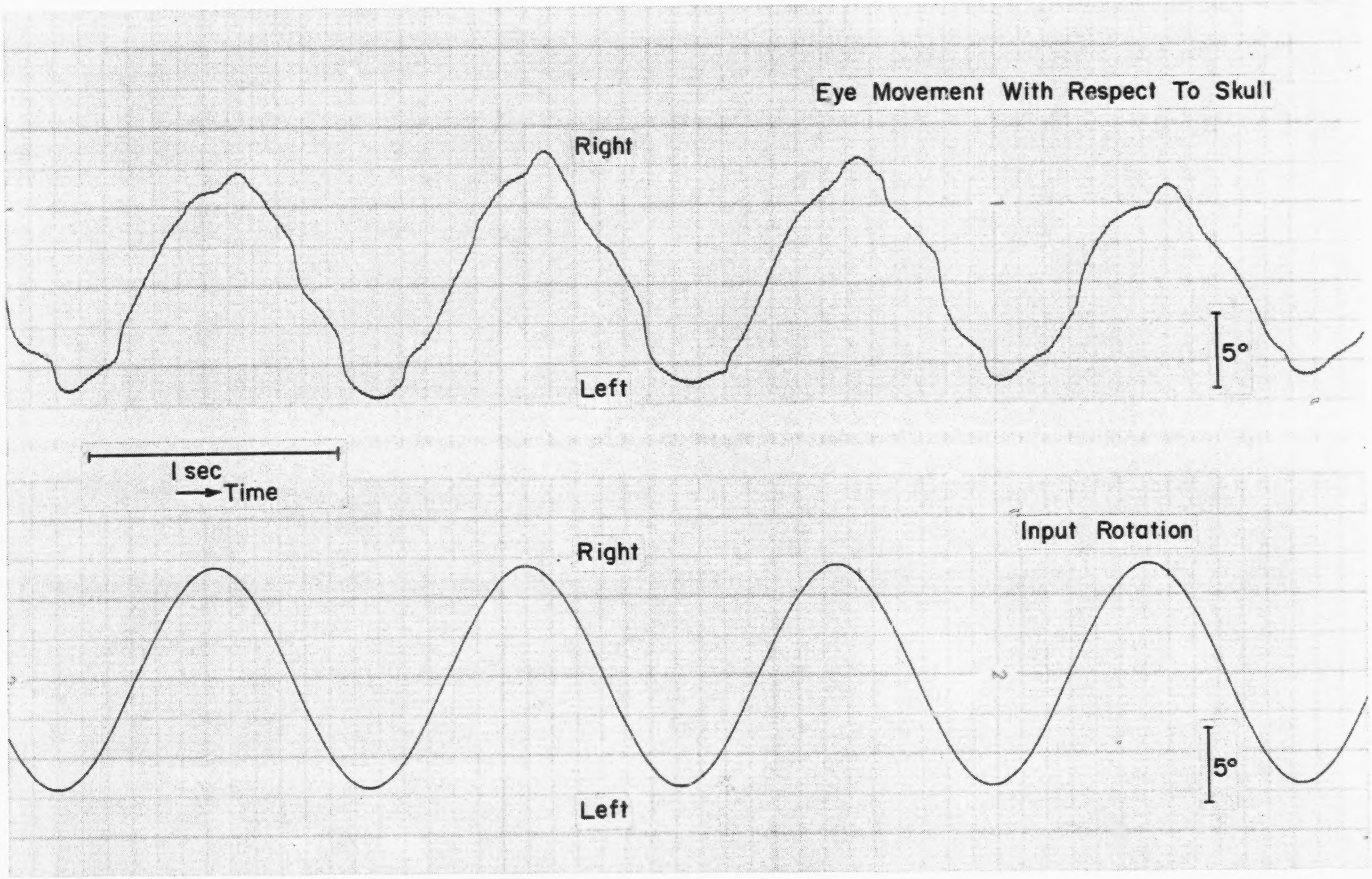

Figure 5.10. Eye Movements, Neck Proprioception and Environmental Fixation Point, f = 0.8 cps

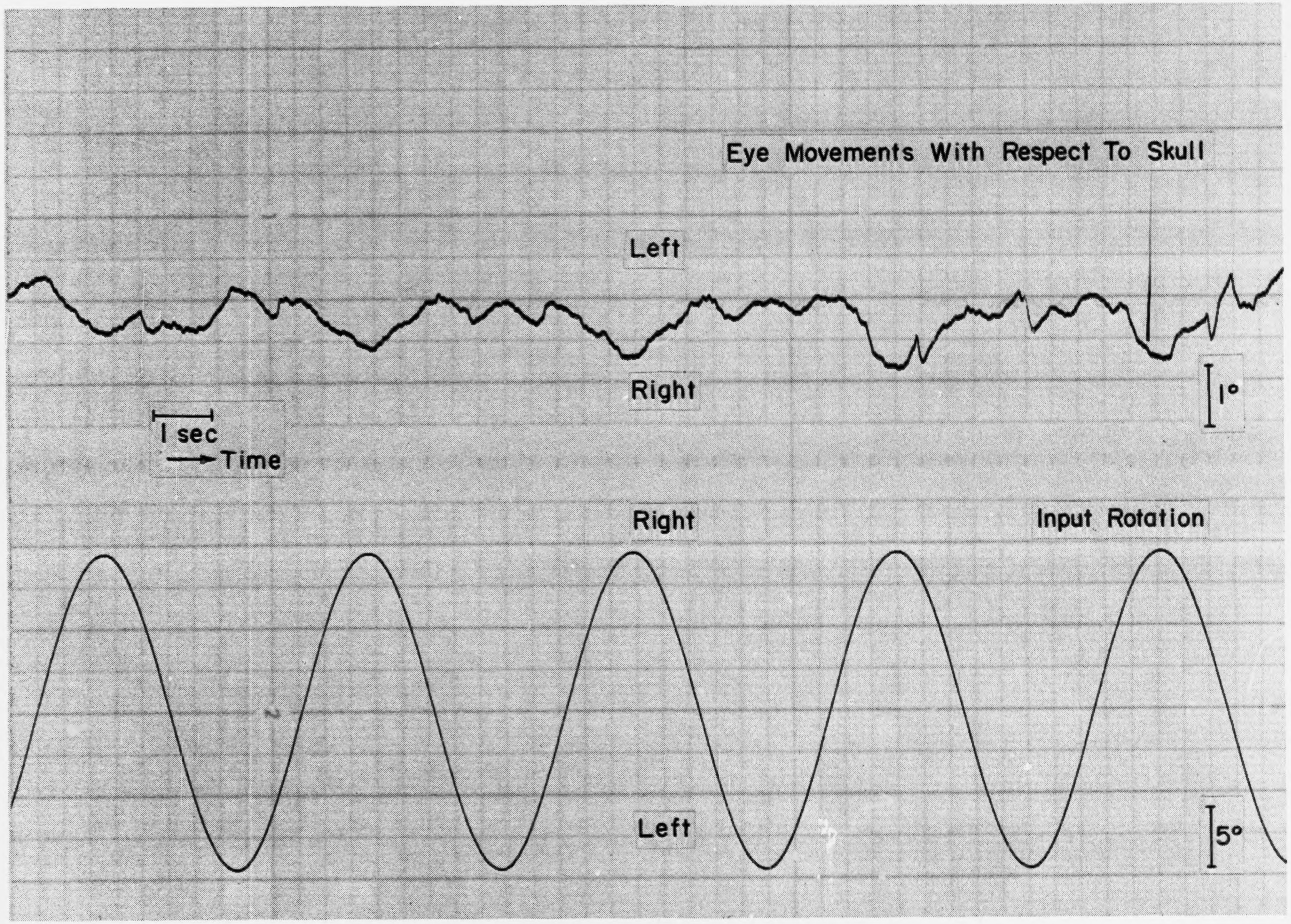

Figure 5.11. *Eye Movements--Neck Proprioception with Earth Fixation Point, f = 0.2 cps*

sinusoidal rotation. The experimental series was carried through in a dark room.

b. Results and Discussion. The recorded data was analyzed by reconstructing the cumulative eye position relative to the head and measuring the respective amplitude ratio and phase lag at any given frequency. A Bode plot of the results with one standard deviation around the mean is presented in Figure 5.12. The sum of the eye-semicircular canals transfer function [Eq. (24)] and the eye-neck proprioceptors transfer function [Eq. (25)] is also shown in Figure 5.12 represented by its straight line approximation. The sum of Eq. (24) and Eq. (25) is given by:

$$\frac{\text{eye velocity } (s)}{\text{input angular velocity } (s)} = \tag{26}$$

$$= \frac{-0.325\ (19.2s+1)(1.12s+1)(0.0067s+1)}{(8s+1)(1.74s+1)(0.04s+1)}$$

Examination of Figure 5.12 shows complete agreement between the experimental data and the predicted response from the separate transfer functions for the vestibular system and the neck proprioceptors. Therefore, the eye movement control system is a linear system at least over the range of frequencies tested here (0.03 cps to 2.0 cps). Since the amplitude ratio is between 0.35 and 0.55 for the frequency range from 0.02 cps to 2 cps, the compensation is only partial and the preservation of a stationary image on the retina without the participation of visual tracking is impossible. The relative contribution of the vestibular system in the resultant compensatory eye movement is larger compared to that of the neck proprioceptors at frequencies above 0.2 cps while below it, the effect of both systems is approximately equal.

Environmental and Earth-fixed Fixation Points. Rotations of the skull in the presence of a fixation point is the most common pattern of maneuvers, during which the eye movement control system is called upon to stabilize the eyeball on a given object. For such rotations, all the loops of the control system are activated, thus the response of the system is the ultimate of stabilization the eye can achieve.

Experiments done here show the total travel of the eye in the presence of an environmental fixation point to be at the maximum of ±0.5 degs. And for earth-fixed fixation, the frequency response of the control system shown in Figure 5.13 exhibits good compensation capabilities over the whole spectrum of frequencies up to 2.0 cps. The phase angle for visual tracking of predictable sinusoids (177) is also shown on Figure 5.13. Note the distinct contribution of the vestibular system and the neck proprioceptors in reducing the phase lag of the eye at high frequencies.

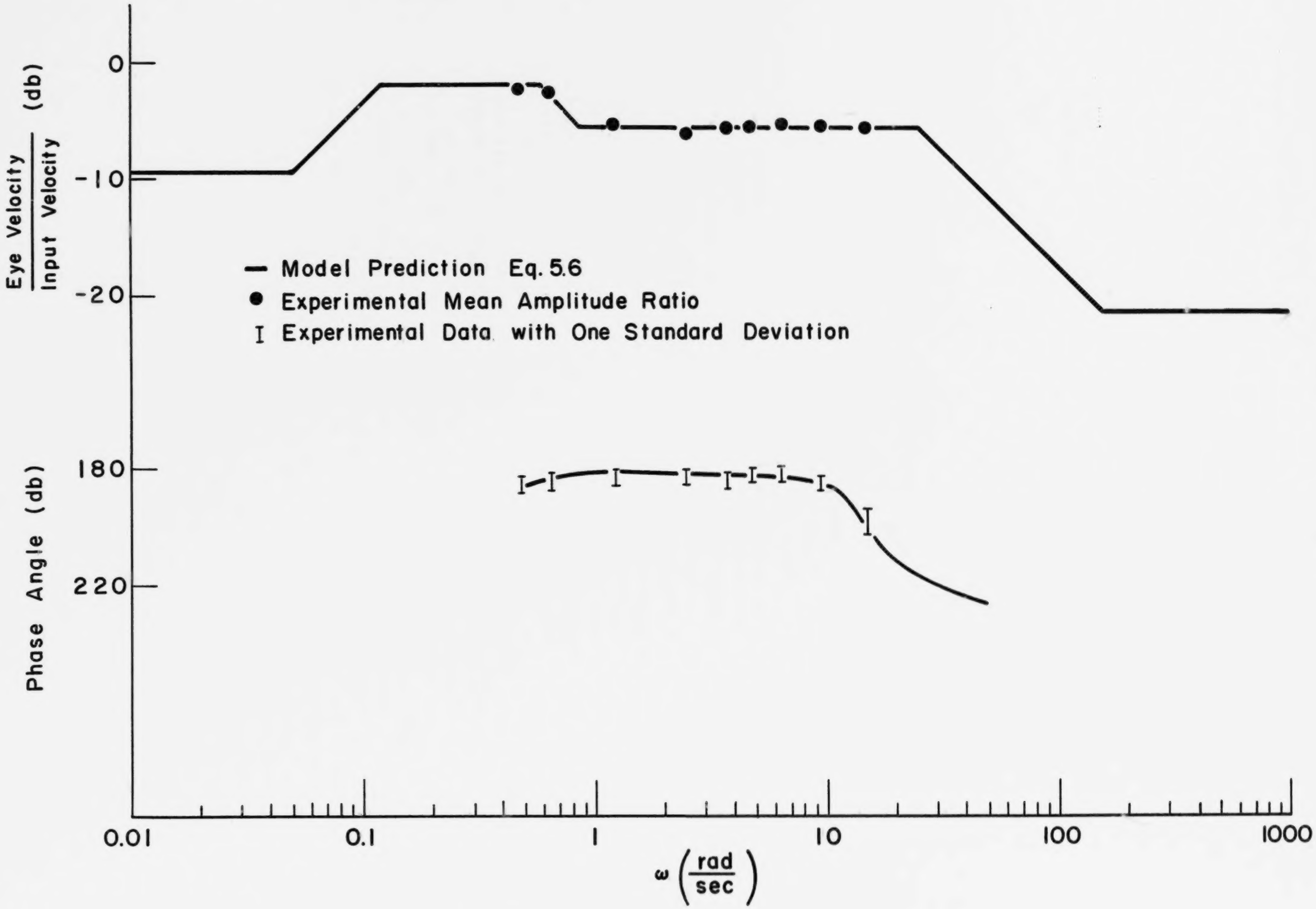

Figure 5.12. Bode Plot of Compensatory Eye Movements (Vestibular and Neck Proprioception)

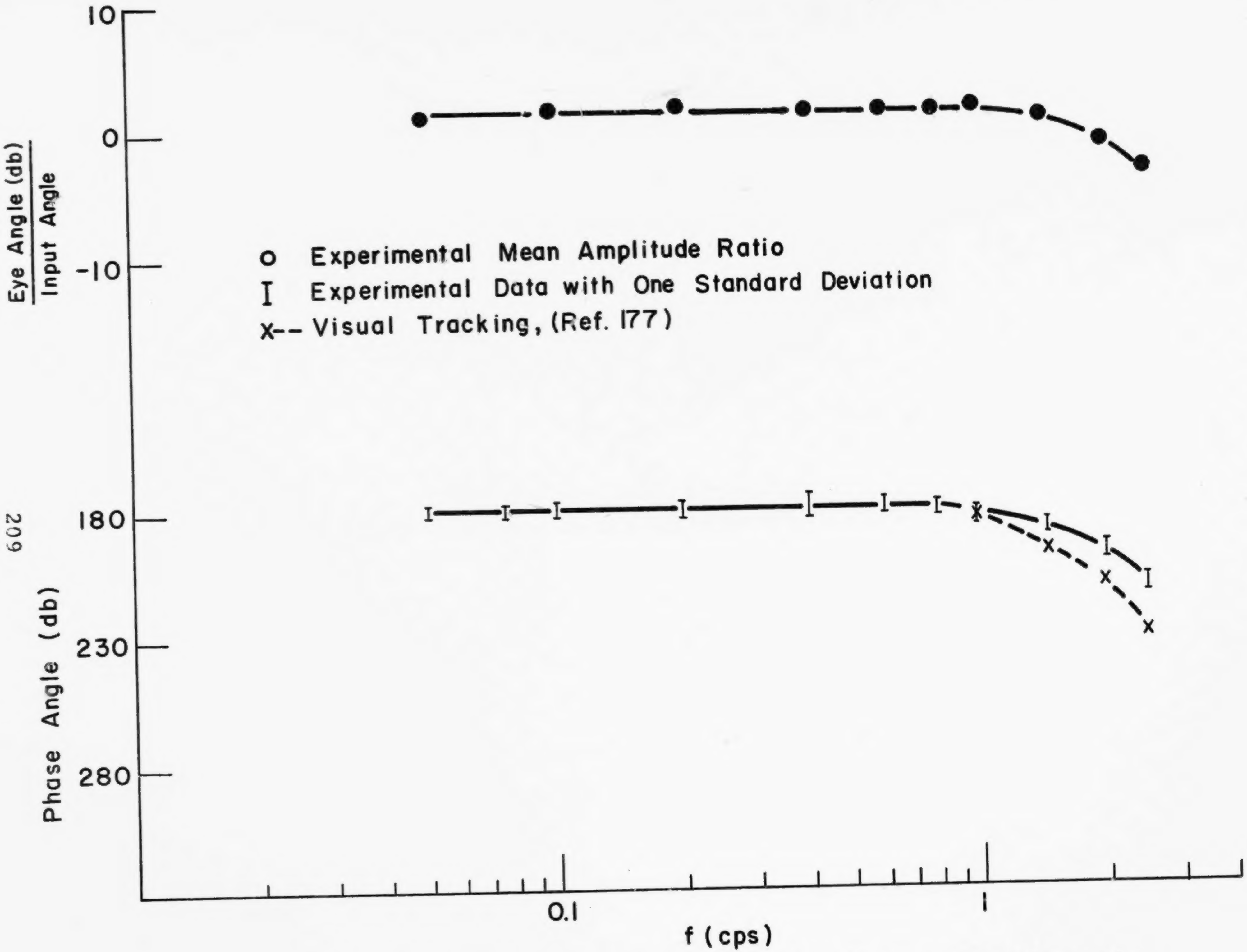

Figure 5.13. Bode Plot of Eye Movements (Vestibular, Proprioception and Earth-fixed Fixation Point)

Stabilization of Eye Position in Space

The eye movement control system as presented in the block diagram of Figure 5.1 consists of three branches, each of which contributes to the control of the eyeball position relative to the skull and the environment. The compensatory eye movements attributed to the vestibular system and the neck proprioceptors are of the nature of reflex responses with no voluntary control upon them. Tracking movements, on the other hand, depend upon the wish to maintain a certain object, in the immediate vicinity, under observation. Regardless of their origin, eye movements during periods of motion disturbances are controlled to keep the eye position stationary with respect to an environment which is judged as stationary too.

Table 5.1 summarizes qualitatively the experimental results obtained in the series of experiments performed here. In the presence of fixation points, rotation of the skull with respect to the body or rotations of the body as a whole, tend to displace the stationary picture observed by the eye. The experiments show that the eye is stabilized in space within ±0.5 degs when the fixation is on the moving surrounding. And for an earth-fixed fixation point, the eye compensates with essentially a constant amplitude ratio and minimal phase lag in response to input frequencies of rotations up to 2 cps. Figure 5.14 is the mathematical model for the horizontal eye movement control mechanism. It incorporates the visual tracking model proposed by Young (177), and the dynamic characteristics of the semicircular canals and the neck proprioceptors, when related to compensatory eye movements as measured here. The linearity of the summing point prior to the motor mechanism of the eyeball was established experimentally for addition of vestibular and proprioceptor signals. Therefore, the assumption of additive property for the visual tracking branch too is plausible and experiments show quantitatively such behavior.

The eye movement model was simulated on an EAI TR48 computer and the response of the simulated system was compared with the experimental results. The model reproduced very well the measured eye movements in the presence of visual fixation. Without this fixation, the "cumulative" eye position only ("fast" phase was not simulated) was obtained.

The performance capabilities of the eye as an orientation sensor can be derived from the model presented here for any maneuver involving rotation around a vertical axis. Comparison of eye movements with an earth fixation point, with and without the participation of the vestibular system, in the control loop outlines the contribution of this system toward stabilization of the eye. With the vestibular system stimulated, eye movements are smooth and regular, free of harmonics. When the vestibular system is unstimulated, eye movements' wave shape loses similarity to the input sinusoid for frequencies above 0.8 cps. The visual tracking loop alone, which is a position

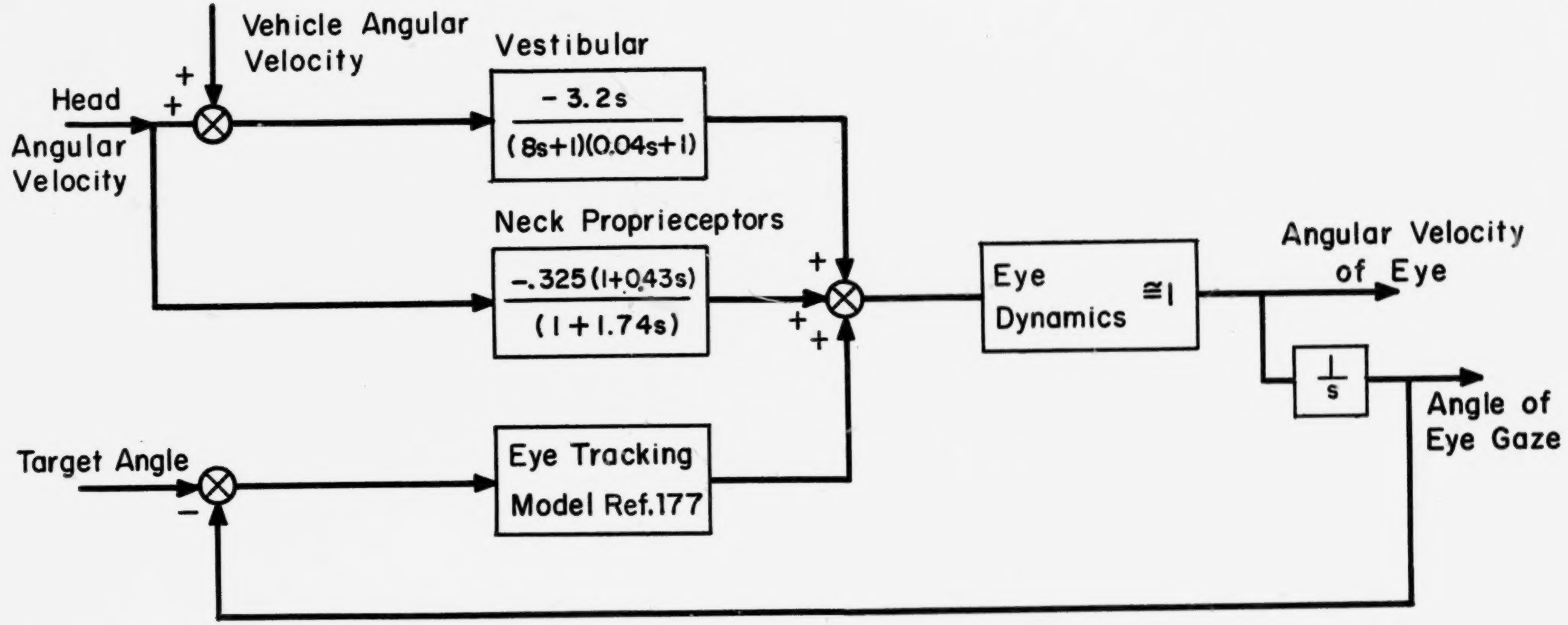
Head Angular Velocity
Vehicle Angular Velocity
+
+
Vestibular
- 3.2s
(8s+1)(0.04s+1)
Neck Proprieceptors
-.325(1+0.43s)
(1+1.74s)
Target Angle
-
Eye Tracking Model Ref.177
+
+
+
Eye Dynamics ≅1
Angular Velocity of Eye
1/s
Angle of Eye Gaze

Figure 5.14. Model for Multi-input Horizontal Eye Movement Control System

control system, shows similar distortion of the wave shape of eye movements for high input frequencies (177). However, with the vestibular system stimulated and with visual fixation, the wave shape regularity of eye movements is preserved for input frequencies close to 2.5 cps. In view of these findings and considering the semicircular canals as angular velocity meters, one can conclude that the vestibular system provides the rate information for the eye movement control system, while the visual tracking monitors mainly the deviation of the eye from a given fixation point.

Table 5.1

Space Stabilization of Eye

	No Fixation Point	*Environmental Fixation*	*Earth-fixed Fixation*
Vestibular	Partial compensation of rotational rate over frequencies from 0.02 cps to 4.0 cps	Maintain eye angle within ±0.5° up to 2 cps	Full compensation up to 2 cps
Neck proprioceptors	Partial compensation of rotational rate below 0.15 cps	Poor compensation above 1 cps	Maintain eye angle within ±0.5° up to 2 cps
Vestibular and neck proprioceptors	Partial compensation of rotational rate up to 4.0 cps	Maintain eye angle within ±0.5° up to 2 cps	Full compensation up to 2 cps

6. SIMPLE MANUAL CONTROL SYSTEMS WITH MOTION INPUTS

A manual control system is a closed loop system in which the human operator attempts to reduce the system error. In a single axis, compensatory tracking loop, the operator perceives the system error only and affects the system output by manipulating a control stick (Fig. 6.1). The mathematical representation of the operator's response for a given task is generally assumed to fit a quasi-linear description (129, 50). Thus, the model of the human operator contains a "describing function" linearly correlated with the system error, and an additive remnant uncorrelated with it. The ability of the human operator to adapt his response to the system inputs and to the controlled elements provides the manual control systems with a desirable flexibility. However, this feature also prevents a unique presentation of the transfer characteristic of the operator since his dynamic response is a function of the control system parameters. Nevertheless, a tabulation of describing functions for various system conditions, is of great importance to the preliminary design of manual control systems.

The Vestibular System As an Input Channel in Manual Control System

The human operator in a vehicle orientation control loop receives the necessary information for his control decisions through a visual display, by motion sensing, or by means of audio communication. Describing functions have been obtained by others for manual control systems in a single axis compensatory task with visual input and manual output covering a wide class of controlled elements (129).

In a vehicle control loop, the operator always receives motion inputs when seated in the vehicle. The effect of these motion cues on the operator's characteristics is, in general, acknowledged (150, 53). However, their contribution to the operator's ability to generate lead compensation and to satisfactorily control a closed loop system have not been assessed prior to this investigation.

Consider the restricted case of control of vehicle orientation to a stationary reference frame. Nonvisual perception of motion in the human is provided by the vestibular sensors, supplemented by tactile and kinesthetic sensations. The vestibular sensors perceive the resultant angular accelerations and specific forces acting on the man in the vehicle. The motion inputs the operator senses are, therefore, compatible with the definitions of a compensatory tracking task for a stationary reference.

Vehicle motions combine rotations and translations stimulating both the semicircular canals and the otoliths. However, an experimental situation can be simulated where motions are classified according to three categories: (*1*) pure rotational

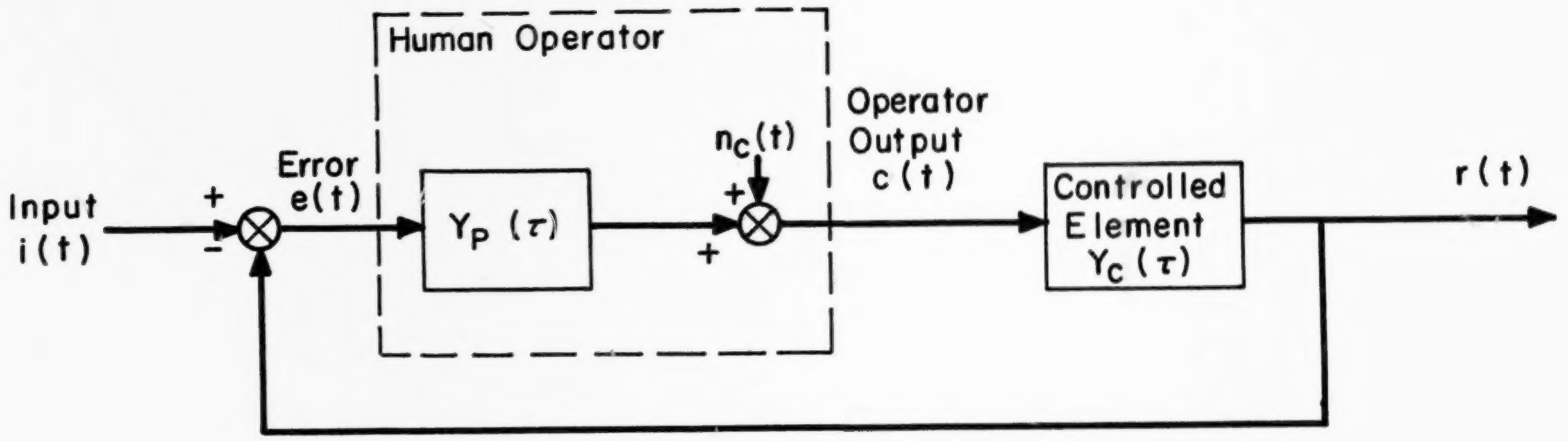
Human Operator
Input
i(t)
+
-
Error
e(t)
Y_P (τ)
n_c(t)
+
+
Operator
Output
c(t)
Controlled
Element
Y_c (τ)
r(t)

Figure 6.1. Block Diagram of Simple Compensatory Manual Control System (Ref. 129)

motion in the horizontal plane; (2) pure translation; and (3) rotational motion with respect to the gravity vector. Under these simulated conditions, angular, linear, or combined accelerations are perceived by the human. They provide the desired separation between the orientation information of the semicircular canals and the otoliths.

In a typical manual control system, the human operator will attempt to maintain some reference orientation in the presence of a disturbance. The block diagram in Figure 6.2 represents the manual control system simulated for this study of the vestibular system in simple, compensatory tasks. The dynamics of the vehicle in the system were a single integration, presumably the optimum one for the operator to control. In this system, operator stick displacement is proportional to vehicle velocity. The human operator may have three modes: visual, motion, or combined. He attempts to control his vehicle to a preset reference in the presence of orientation disturbances.

The characteristics of the human operator in these manual control systems were analyzed in terms of quasilinear describing functions. The identification technique outlined in Appendix D defines the transfer function of the human operator as:

$$Y_p = \frac{\Phi_{ic}(\omega)}{\Phi_{ie}(\omega)} \qquad (27)$$

where $\Phi_{ic}(\omega)$ = cross power spectral density of input and operator's output and

$\Phi_{ie}(\omega)$ = cross power spectral density of input and system error.

For the experimental manual control system, the input is the noise disturbance, and the system error is the deviation of the vehicle orientation from the reference. A measure of the similarity of the human operator's transfer characteristics to a linear element is provided by the square of the linear correlation, ρ, given by:

$$\rho^2 = \frac{|\Phi_{ic}|^2}{\Phi_{ii}\,\Phi_{cc}} = 1 - \frac{\Phi_{nn}}{\Phi_{cc}} \qquad (28)$$

where $\Phi_{nn}(\omega)$ = the remnant power spectral density,

$\Phi_{ii}(\omega)$ = the input (disturbance) power spectral density, and

$\Phi_{cc}(\omega)$ = the human operator's response power spectral density.

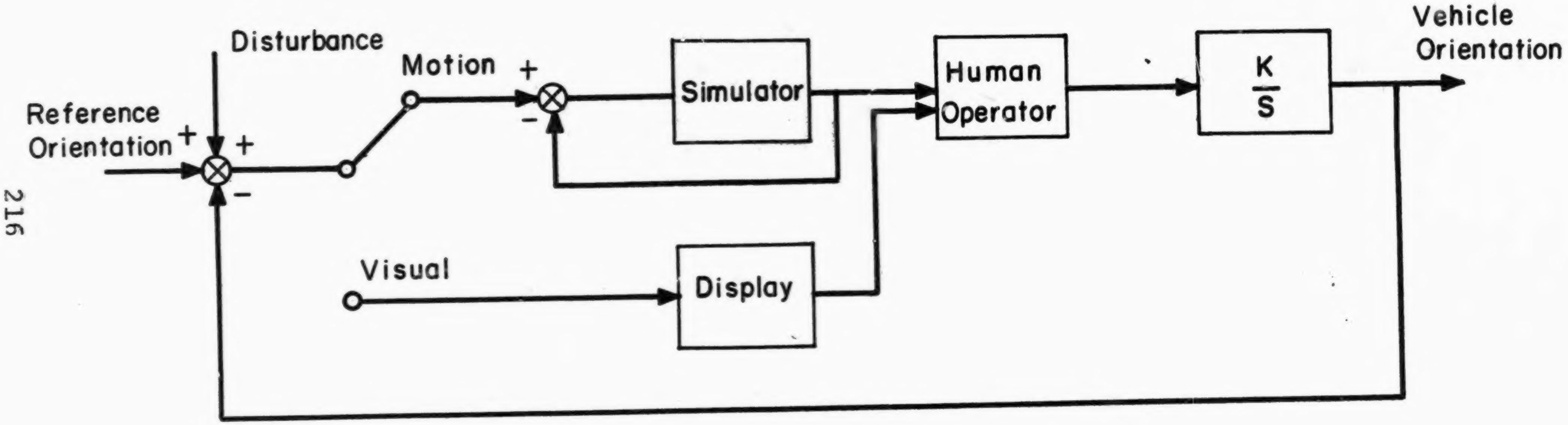
Disturbance
Reference Orientation
+
+
−
Motion
+
−
Simulator
Human Operator
K/S
Vehicle Orientation
Visual
Display

Figure 6.2. Velocity Control with Visual or Motion Mode

A value of ρ^2 near unity implies that the operator's remnant is small compared with his output, which is correlated with the system input. In a manual control system with a stochastic disturbance, to avoid prediction, the measured operator's characteristics are closely approximated by the calculated transfer functions.

The disturbance input in this experimental series was filtered Gausian noise, generated by a noise generator, with a constant power spectral density from DC to 50 cps. This noise was shaped with two cascaded first order filters, with corner frequencies at 0.15 cps, while its rms amplitude was adjusted for each experimental condition.

A Manual Control System with Pure Horizontal Rotation

Rotation of a vehicle about the gravity vector (yaw) is a control situation where the otoliths can be maintained unstimulated by linear accelerations, except for the ever present gravity field. If the head of the subject is placed in the axis of rotation of the simulator, and maintained fixed with respect to the moving cab, the centrifugal and the tangential accelerations arising from the rotational motion can be minimized.

The block diagram of Figure 6.2 points to three modes for the human operator, all of which were investigated here: (*1*) visual display with no motion, corresponding to a fixed base control system; (*2*) vestibular information with no visual display; and (*3*) combined visual display and vestibular sensation of motion.

a. Method: Manual control of attitude was performed driving a moving base simulator about its vertical axis. In the rotating cab of the simulator, an oscilloscope displaying a vertical line provided the visual, compensatory input. The operator, strapped to his chair, had his head supported with a headrest. He exercised control on the system with a lightweight, spring restrained, linear stick, mounted beside his seat for right hand manipulation. The experimental parameters were

white noise disturbance--15° rms

visual display--2/15 inch/degree of rotation

control gain--K = 0.5 deg/sec/degree of stick

stick--linear, with maximum travel of ±45°, corresponding to velocity command of ±22.5 deg/sec.

In visual and combined modes the operator was instructed to maintain his initial orientation. Two different operator tasks were experimented with, for motion tracking only: (*1*) to keep the vehicle on course; and (*2*) to keep the vehicle stationary. The difference between these instructions is whether or not a correction for accumulated drift, off course, should be introduced by the operator.

Three subjects were used for this experimental series. They had previous experience in operating manual control systems and were trained for the experimental tasks. Each subject was scored on 10 runs of 90 seconds duration for each experimental condition.

b. Results: For each run of the visual and visual-motion tracking, the noise disturbance, system error, operator's output, and integrated stick output were recorded on magnetic tape, converted to digital form, and processed by an IBM 7094 digital computer. The describing functions for the human operator were determined by the identification procedure outlined in Appendix D. These results were averaged for each subject yielding the mean amplitude ratio and the phase angle versus frequency. Standard deviation of these were also evaluated. The correlation coefficient at any given frequency was determined. Results with $\rho^2 < 0.75$ were dropped because the assumption of quasilinearity becomes poor. This procedure provided experimental describing functions in terms of amplitude ratio and phase angle over the frequencies from 0.056 cps to 0.8 cps for each subject.

The describing functions were tested for intersubject differences which were not found to be significant ($P > 0.100$). Following this observation, a theoretical fit to the averaged experimental data was obtained with the results summarized below:

visual input
$$Y_p(s) = \frac{7e^{-0.2s}(2.4s + 1)}{(3.15s + 1)}, \quad \frac{\overline{e^2(t)}}{\overline{i^2(t)}} = 0.075 \qquad (29)$$

visual and motion input
$$Y_p(s) = \frac{7e^{-0.1s}(2.4s + 1)}{(3.15s + 1)}, \quad \frac{\overline{e^2(t)}}{\overline{i^2(t)}} = 0.050 \qquad (30)$$

The describing function obtained for visual input is in good agreement with results published previously (89, 148). At frequencies up to 0.2 cps, the data agree with that of Russell (148). For larger frequencies, the operator's phase lag follows closely the results of Hall (89). Note that Hall used input noise comparable to the disturbance input here.

The experimental compensatory task, with motion sensing only, did not yield any meaningful results in terms of describing functions for the human operator. Subjects were unable to keep the simulator within its travel limits (about ±35°) for periods longer than 25 to 30 secs. During this time, the deviation of the cab off course increased at a steady rate between 1 and 3 deg/sec, with superimposed oscillations representing the control activity of the operator in response to the input disturbance.

c. Discussion: The experimental describing functions and their corresponding analytical approximations point out the significant contribution of motion cues to satisfactory performance in a manual control system. A considerable reduction of operator phase lag is noticed for the moving base simulation relative to the fixed base one (Fig. 6.3). In the analytic transfer function this reduction is expressed as a decrease in dead time delay from 0.2 sec to 0.1 sec. The describing functions are otherwise equal. The conclusion is that the operator is able to reduce his delay time in a manual control system where his semicircular canals provide information on the vehicle motion, compared to the delay in a system with visual display only.

Since the semicircular canals are angular accelerometers, they cannot detect a constant angular velocity. This was demonstrated experimentally in the motion compensatory task where the simulator drifted away from the reference with approximately constant angular velocity. Therefore, complete control of vehicle attitude, including low frequency drift, is impossible by only vestibular sensing of motion. However, when a visual reference is provided, the information originating in the semicircular canals is utilized by the human operator. It was previously shown that over the frequency range from 0.1 rad/sec to 10 rad/sec that the canals are essentially angular velocity meters. Thus, they are a source of rate information for the operator, which he apparently uses to generate lead compensation.

Manual Control System with Linear Motion

In the last section, the observation was made that the semicircular canals alone cannot be used as sensors in a manual control system. A similar statement is true for the otoliths, the human specific force sensors. The difficulty arises from the fact that the compensatory task assigned to the operator in pure linear or rotational motion does not fit the sensing capabilities of the vestibular sensors. The otoliths are insensitive to constant linear velocity. Consequently, a vehicle can drift away with constant linear velocity, and the operator is unable to perceive this motion.

Experimentally, the operator was given velocity control on a linear motion simulator (see Appendix B). The control system was as shown in Figure 6.2 with input noise disturbance of 10 ft, rms, and K = 1.0 ft/sec/deg of stick. With motion inputs only, the operator could not maintain the simulator within its travel limits for more than 40 sec.

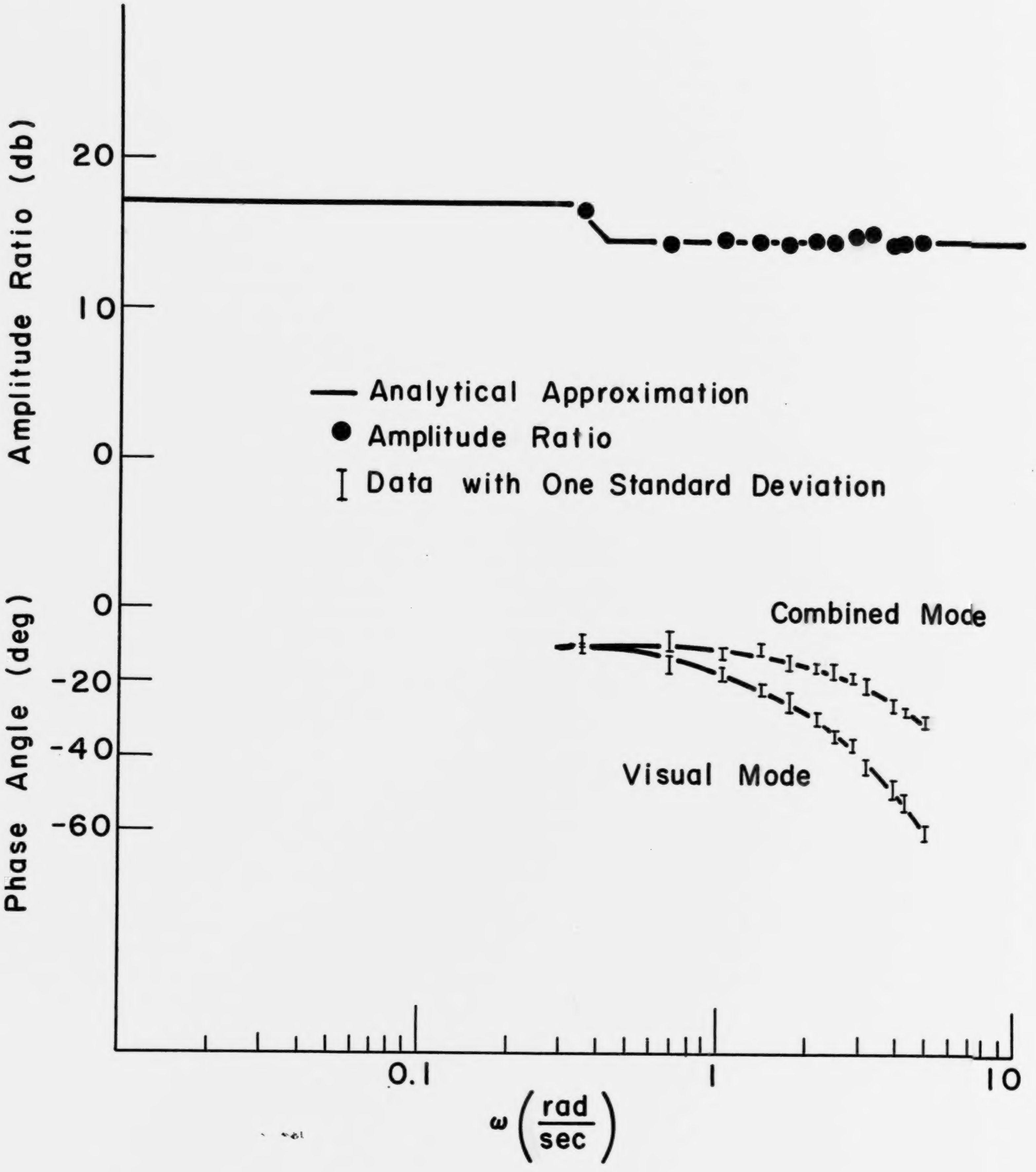

Figure 6.3. Describing Function of the Human Operator in Visual and Combined Mode. Horizontal Rotation.

Control of Motion with Respect to the Gravity Vector

The control of vehicle motion in roll stimulates both the semicircular canals and the otoliths. In this single axis task, the vehicle motion provides sufficient input information for control by the human operator. The otoliths are sensitive to any angular deviations from the vertical gravity vector, and the semicircular canals sense angular rates. The manual control system permits comparison of the effects of various combinations of inputs on the operator's performance.

a. Method: A single axis compensatory task was simulated on the moving base simulator driven about its roll axis. The visual input was an oscilloscope, displaying a line whose angle with the vertical corresponded to the roll angle of the simulator. The operator was seated in the simulator as described before.

The experimental parameters were

white noise disturbance--20° rms

visual display--angle of display corresponds to error angle

control gain--$K = 1.0$ deb/sec/degree of stick

stick--linear with maximum travel of ±45° corresponding to velocity command of ±45 deg/sec

dead time delay of visual display--1 sec

The operator was instructed to maintain the simulator vertical throughout the experimental series. His performance was measured in the following control situations:

(*1*) Rotation with respect to gravity--motion input with hard seat

(*2*) Rotation with respect to gravity--motion input with soft seat

(*3*) Rotation with respect to gravity--motion input and visual indicator

(*4*) Rotation with respect to gravity--motion input and delayed visual indicator

In comparing two control situations differing only in the seat on which the operator sat, an attempt was made to indicate the effect of tactile sensation on the operator's performance. Similarly the study of the control loop with visual indicator, in phase with the motion and delayed, was intended to separate the effect of the visual input from the contribution of the motion cues.

b. Results: The describing functions of the human operator in these control situations were measured and analyzed as described previously. These results are summarized below:

motion input and hard seat $Y_p(s) = 5 \quad \frac{\overline{e^2(t)}}{\overline{i^2(t)}} = 0.045$

motion input and soft seat $Y_p(s) = 5 \quad \frac{\overline{e^2(t)}}{\overline{i^2(t)}} = 0.046$

motion and visual inputs $Y_p(s) = 5 \quad \frac{\overline{e^2(t)}}{\overline{i^2(t)}} = 0.044$

In the control system with motion input and delayed visual indicator, the visual information was delayed with a dead time delay of one second. All the three subjects reported that they discarded this information since it impaired their performance. The describing function of the human operator for this condition, as well as others, was similar to this measured for motion input with hard seat. Note the extent of compensation the operator achieves in this control system. His transfer function is a pure gain, indicating a capability to compensate his phase lag for frequencies up to 0.8 cps.

c. Discussion: As described before, motion information, in absence of visual input, is perceived by the vestibular sensors and the tactile receptors. Here, in an attempt to demonstrate the effect of the tactile sensation on the operator response, his performance was measured in two control tasks differing only in the seat on which the operator sat. In one case, it was a very hard plastic seat, in the other an extremely soft, foam rubber cushion. The hardness of the seat was believed to vary the extent of the perceived tactile sensation. The measured describing functions do not indicate any variation of performance between the two control situations. Similarly, the variation of the ratio of mean square error to mean square input is not significant statistically. The conclusion is that for this experimental situation, the tactile sensation does not have noticeable influence on the operator's ability to perform his task.

A comparison of the operator's characteristics in a system with visual and motion inputs, to those with no visual input, does not show a significant influence of the visual input. Similarly, the fact that the operator was able to distinguish discrepancies between his motion inputs and the visual display, indicates probably that he monitors the display, rather than using it as an input.

The experimental results presented here demonstrate the dominant role of the vestibular sensor in the performance of the operator. In the simulated, manual control system, without specific instructions to the subjects, the visual input is either disregarded, or used as a secondary source of information with small influence on the control decisions of the operator. Note that the describing function of the operator in this control system simulated on a fixed base with visual input would have been approximately

$$Y_p = \frac{3.5e^{-0.2s}(2.4s + 1)}{(3.15s + 1)}$$

based on the measurements described previously.

The performance of the human operator in this vehicle control system is approximately a pure gain. (See Figure 6.4.)

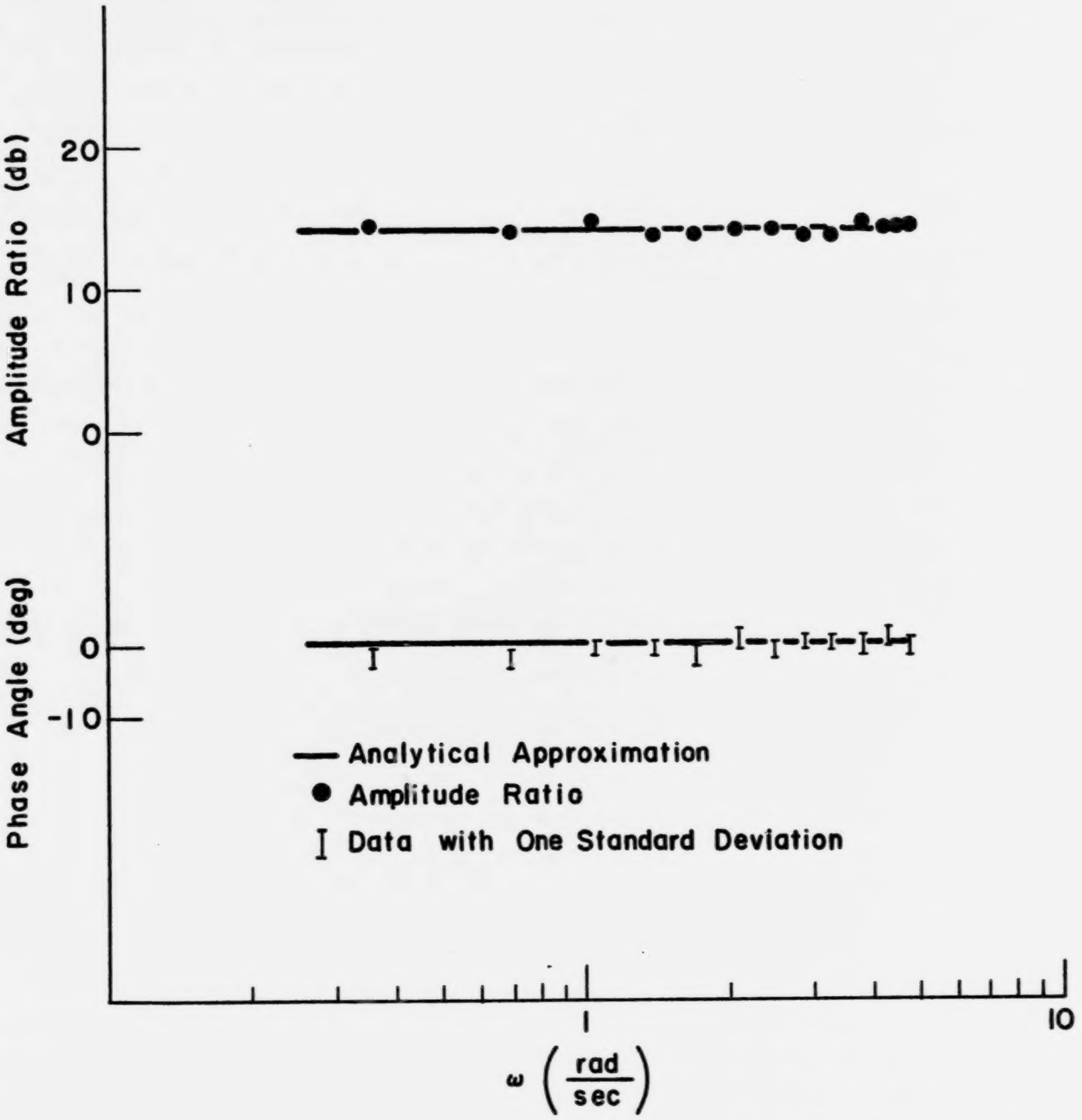

Figure 6.4. Describing Function of the Human Operator in Motion Mode. Rotation with Respect to the Gravity Vector

This approximation indicates that the human operator is able to compensate for his dead time delay and other lags by virtue of sensing motion away from vertical. The motion inputs substantially improve the performance of the human operator compared to his characteristics obtained in a fixed base simulation.

Summary

The characteristics of the human operator were measured in a simple manual control of vehicle orientation. It was verified that the operator cannot use motion inputs alone for satisfactory control when his sensors do not receive a constant reference stimulus. The vertical is the only reference with respect to which the human can establish his orientation. Therefore, the conclusion follows that control of vehicle orientation to the vertical is the only orientation task the human can perform with the vestibular system as sole input sensor. The presence of motion cues in a simple compensatory control task provides the operator with information which greatly improves his control characteristics.

7. VISUAL AND VESTIBULAR CONTROL OF AN UNSTABLE SYSTEM

In section 6, simple manual control systems were investigated and "describing functions" for the human operator were presented. There, a substantial difference in performance of the operator was found when systems with visual input only were compared with systems with motion inputs or visual and motion inputs. For identical system parameters, the describing function of the operator measured with motion inputs exhibits large reduction of phase lag relative to the characteristics obtained with a fixed base simulation. This observation, which is an indication of the compensation capabilities of the human, was attributed mainly to the rate information the operator receives from his vestibular sensors. The results, although convincing, did not establish quantitative comparison of the lead compensation abilities of the operator related to the nature of inputs he perceives.

By experimenting with control situations involving unstable systems, in which the operator had visual or motion inputs or both, it was hoped to isolate and identify his compensation characteristics.

Control of an Unstable System

Method. The control of the deviation from the vertical of a moving base flight simulator (see Appendix A) driven about its roll axis, simulated a single-axis compensatory tracking task for the human operator.

Three control situations, (*1*) visual, (*2*) motion, or (*3*) combined visual and motion, were studied for identical external loop characteristics as illustrated in Figure 7.1. For the visual experiments the subject was outside the simulator, seated 10 ft away from it. A reference marker, mounted horizontally on the moving cab, aided the operator in judging any tilt of it with respect to the laboratory background. For the motion experiments, the operator was forced to utilize the sensing capabilities of the vestibular system and the pressure sensing tactile sensors to control orientation to the vertical. The subject was seated in the moving cab, strapped to his chair, with head supported and fixed in order to control inputs to the vestibular mechanism. The simulator cab was covered with a lightproof hood, no instruments were used inside the cab and the interior was not lighted. The subject was seated and supported in a similar manner for the combined visual and motion cues study except that the cab hood was removed. Crossed horizontal and vertical reference lines were taped to the laboratory wall facing the simulator, at subject's eye level and at a distance of 10 ft.

The reference orientation was the vertical, and the operator was instructed to maintain this orientation for all the experiments. No external input signal (disturbance) was fed into the control loop. Control of self-induced errors with unstable controlled elements imposes sufficient difficulty and challenge for the operator.

The simulated controlled element was of the form

$$\frac{A\omega_d^2}{s^2 - \omega_d^2}$$

representing an undamped inverted pendulum. ω_d^2 took the discrete values of 0.5, 1, 2, 3, 4, and 5, where higher ω_d represents a more difficult element to control because of faster divergence of the system. The gain A was set at the constant value $A = 2$, for all experiments. The operator exercised acceleration control on the system with a light, spring-restrained stick. The control stick was linear with maximum travel of $\pm 45°/\text{sec}^2$, thus having maximum specific torque capability ($A\omega_d^2$) in the range of $\pm 45°/\text{sec}^2$ up to $\pm 450°/\text{sec}^2$ depending upon the system characteristics; greater control power associated with more divergent systems.

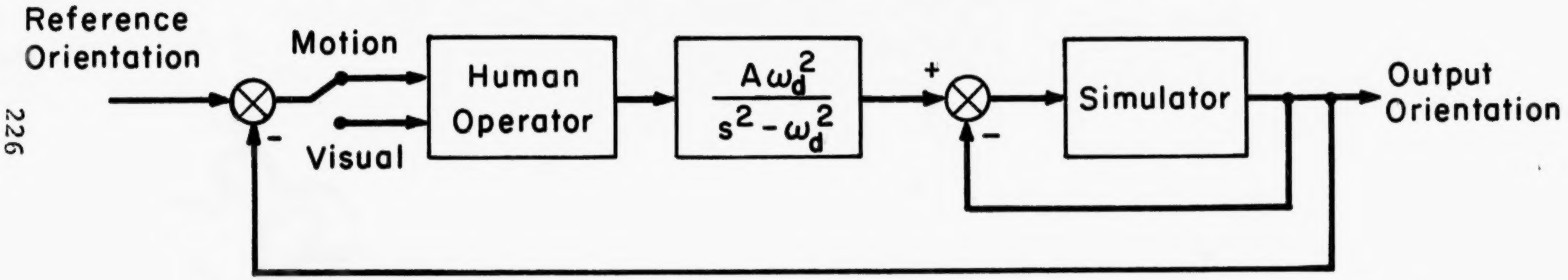
Reference Orientation
-
Motion
Visual
Human Operator
$\frac{A\omega_d^2}{s^2-\omega_d^2}$
+
-
Simulator
Output Orientation

Figure 7.1. Control of Inverted Pendulum with Visual or Motion Feedback

The flight simulator was driven as a position servo about its roll axis. Its dynamics up to 1 cps can be described as a time delay ($e^{-0.1s}$) and are neglected for the purpose of this investigation.

Three subjects with previous tracking experience were used in these experimental series. They were trained in control of the simulator in the visual and motion mode for one half hour during which their performance was monitored. After reaching a relative plateau of proficiency, five scoring runs for each value of ω_d^2 in ascending order, were recorded. The runs were 90 sec long, taken after a 30-sec "warm-up" period. Resting periods of at least 90 sec were allowed between consecutive runs.

Results. The simulator roll angle (deviation from the vertical) and control stick output (human operator response) for each run were recorded on magnetic tape and paper recorder. Inspection of this data reveals some obvious characteristics of the control loop.

The tracking record shown in Figure 7.2 was taken for visual control tracking conditions at $\omega_d^2 = 2$. Changes in the divergence frequency or tracking conditions primarily affect the error amplitude.

The deviation from the vertical, shown as the upper trace of the recording, points to the fact that the operator maintains good control of the system. No uncontrollable divergence is found, and when excess deviation develops, the system can be brought under control by the operator. The low frequency oscillations observed are characteristic for the loop. This system behavior is sufficient evidence that the human operator develops compensation needed to stabilize the loop.

The operator's control movements represented by the command accelerations shown in the lower tracing of the record are of the bang-bang type, with no indication of fine corrections around the zero level, despite his exercise of control through a linear stick. This response of the operator is of distinct nonlinear nature resembling the output of a relay or 3-mode switch. The total stick travel is kept approximately constant with controlled element variations, indicating a linearly increasing specific torque related to ω_d^2.

Examination of the tracking records is rather revealing. The lead compensation capability of the operator is well demonstrated by the stability of the closed loop. It is also noted that the human operator is adapting to the difficult control task by resorting to a fairly nonlinear output. The on-off or bang-bang response of the operator under these conditions can be considered an independent feature of his, rather than being forced to use it by design of the controller.

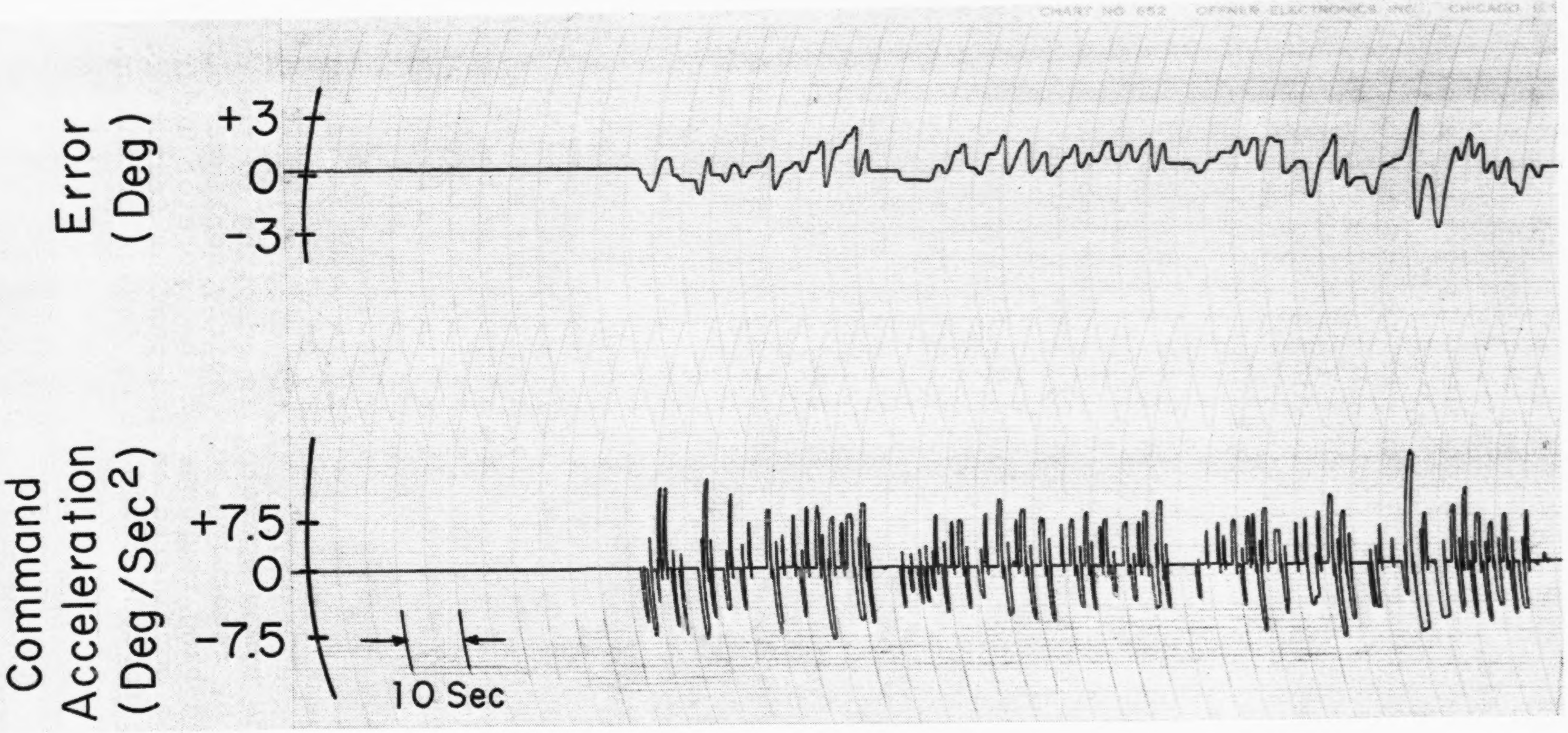

Figure 7.2. Time-Record-Control of Inverted Pendulum Showing Bang-Bang Use of Linear Controller

An On-Off Model for the Human Operator

The analog description of the human operator should preserve the nature of his control mode (linear, bang-bang) along with a presentation of equivalent electromechanical networks. By virtue of this method, engineering analysis of loop behavior will resemble the actual control situation in overall performance and in addition will allow simulation of expected human response.

In view of the control loop characteristics just discussed, an on-off model for the human operator might be considered. Since the major contribution of the operator is the provision of lead equalization, a model such as given in Figure 7.3 may be a sufficient description of the human operator. Here he is assigned a reaction delay, and permitted to generate lead, but is restricted to three output levels. A remnant term $N(s)$ accounts for uncertainty in triggering of the switch. With no disturbance, the on-off control model and second order controlled element are amenable to analysis in the phase plane (144, 68). The representation is one of a controller whose nature is known, but its associated characteristics (rate compensation and delay time) have to be determined. This information is provided by the switching lines, the locus of roll angle and roll angular velocity (error and error rate) at which the operator would switch polarity of his command.

To use phase plane for data analysis, the recorded data for each run was converted to digital form and processed in an IBM 7094 computer where smoothed error (e) and error rate ($\dot{e}$) were computed. An experimental trajectory on the e-$\dot{e}$ plane, picking up at the point (-3.8, 0) and lasting for approximately 10 sec, is shown in Figure 7.4. Notice the general shape of the trajectories centered about regions near the origin and leading to a limit cycle type of behavior.

After computing the error and error rate, the computer searched the record of the stick position for sign changes and defined those as switching points. It was found that only a small percentage of transitions were to the zero level (6 percent); also the average time for completion of a transition is of the order of 0.4 sec. On the basis of these findings, two assumptions were made for future analysis: (*1*) the human operator behaves like an ideal relay, and (*2*) his characteristics are described by a set of intended switching lines.

An intended switching line is a locus representing switching points where the operator intended to switch (about 0.4 sec before the actual torque reversal). If his control activation were that of an ideal relay, the control torques would have reversed along this locus. The intended switching lines together with the specific torque levels completely define the model for the human operator in this control loop.

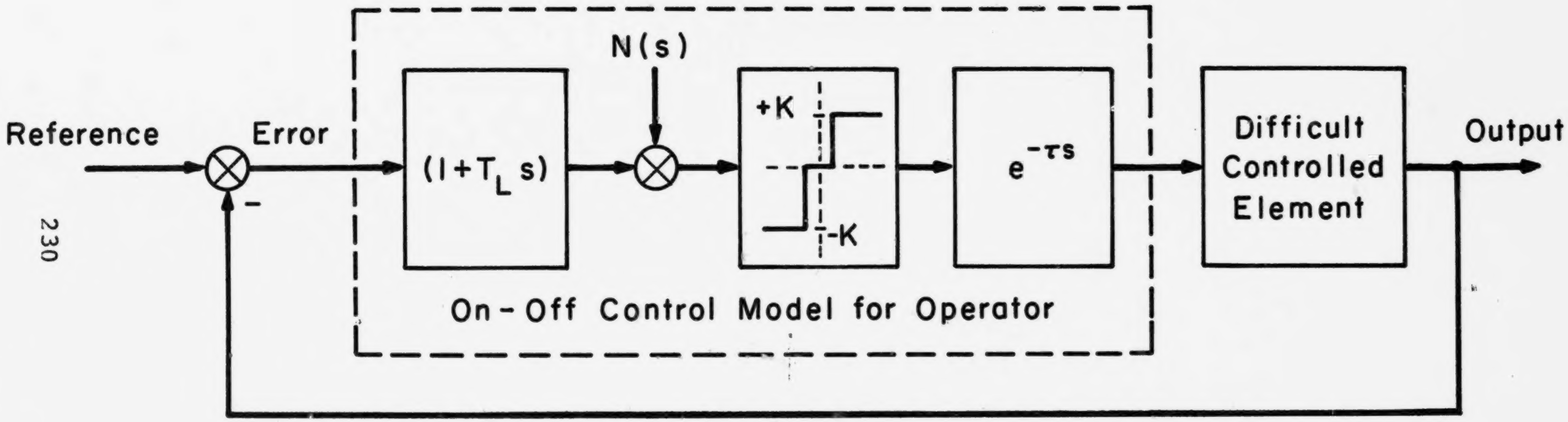
Reference
Error
-
N(s)
(1+T_L s)
+K
-K
e^{-τs}
On-Off Control Model for Operator
Difficult
Controlled
Element
Output

Figure 7.3. Proposed On-Off Control Model for Human Operator in "Difficult" Control Task

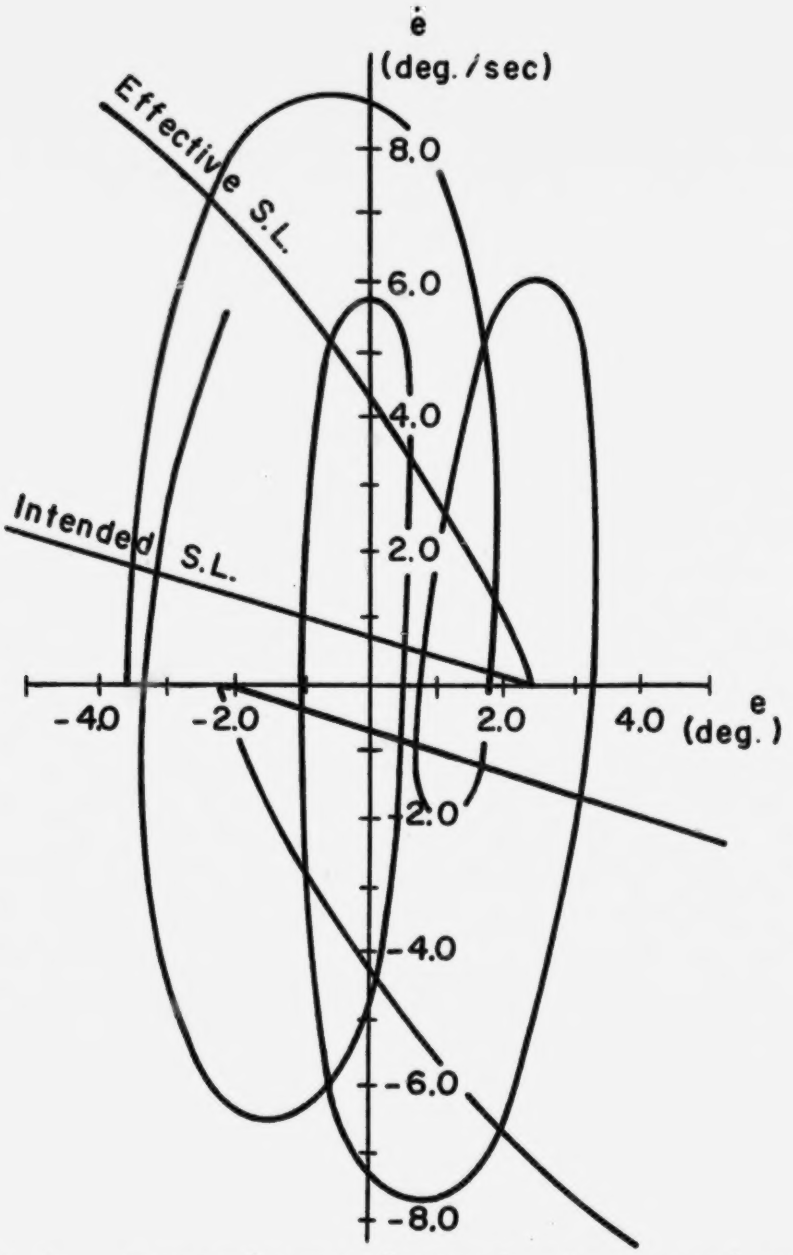

Figure 7.4. Experimental Trajectory and Switching Lines

A least squares curve fit was used to approximate regression lines in the second and fourth quadrant for the intended switching line coordinates (141). First order and second order polynomials of e and $\dot{e}$ were fitted, with the criteria for acceptance based on the value of χ^2 (chi square) distribution. With significance of 1 percent or better, the straight line regression was found to be sufficient representation of the intended switching lines. The parameters of the intended switching line, its slope and intercept with the $\dot{e}$ axis, are significant in terms of the proposed on-off model for the human operator. For controlled element dynamics of pure inertia, the switching lines equation is (68)

$$\dot{e} = -\frac{e}{T_L-\tau} \pm AK\omega_d^2 \frac{\tau(2T_L-\tau)}{2(T_L-\tau)} \qquad (31)$$

where T_L is the lead equalization time constant and τ is the dead time delay. The use of this equation is a justified approximation since the dynamics of the loop for this series of experiments resemble those of a pure inertia when small roll angles are considered. The intended switching lines are the straight lines shown in Figure 7.4. From these intended switching lines one observes that the operator was indeed using lead compensation and that a dead time delay breaks the switching line into two segments which do not pass through the origin. However, calculation of theoretical trajectories based on a switching model for the operator requires the use of the effective switching lines rather than the intended switching just discussed. The effective switching lines are shown in Figure 7.5 and are computed from the intended switching lines by advancing the switching points along the phase portrait by 0.4 sec from the intended switching lines previously calculated. This advance represents the average distance the system has progressed along its trajectory from the time of the beginning of a control transition until this reversal was completed. A theoretical trajectory starting at the point (-3.8, 0) as in the experimental trajectory of Figure 7.4, and calculated on the basis of the effective switching lines, is shown, superimposed on these switching lines in the phase plane, of Figure 7.5. The resemblance of the two trajectories, both in size of the approximate limit cycle and general shape, provides encouraging support for the use of an on-off model for the human operator in this control situation.

Note the conceptual difference between the switching lines. The intended switching line is characteristic of the human operator and his model representation. It specifies the lead equalization time constant the pilot will utilize in a given control situation. On the other hand, the effective switching line is a curve dependent upon the controlled element and the operator's control actions. Due to an average lag in executing his decision to reverse polarity of control, the pilot will allow the system to travel up to the effective switching line before a complete torque reversal is achieved. It is obvious then that the locus of effective switching points will vary with the dynamics of the controlled system.

The statistically fitted lines can be compared to the theoretical equation [Eq. (31)] and values of lead time constant and dead time delay are evaluated.

The mean slope and the mean intercept for each ω_d and each experimental condition were computed and tested for one percent significance by the difference of matched pairs test (140, 141). These statistical tests were evaluated for different values of ω_d under the same tracking conditions (visual, motion, or combined) and for similar values of ω_d among three classes of control. The slope of the intended switching line, $-1/T_L - \tau$, is an indication of the amount of lead

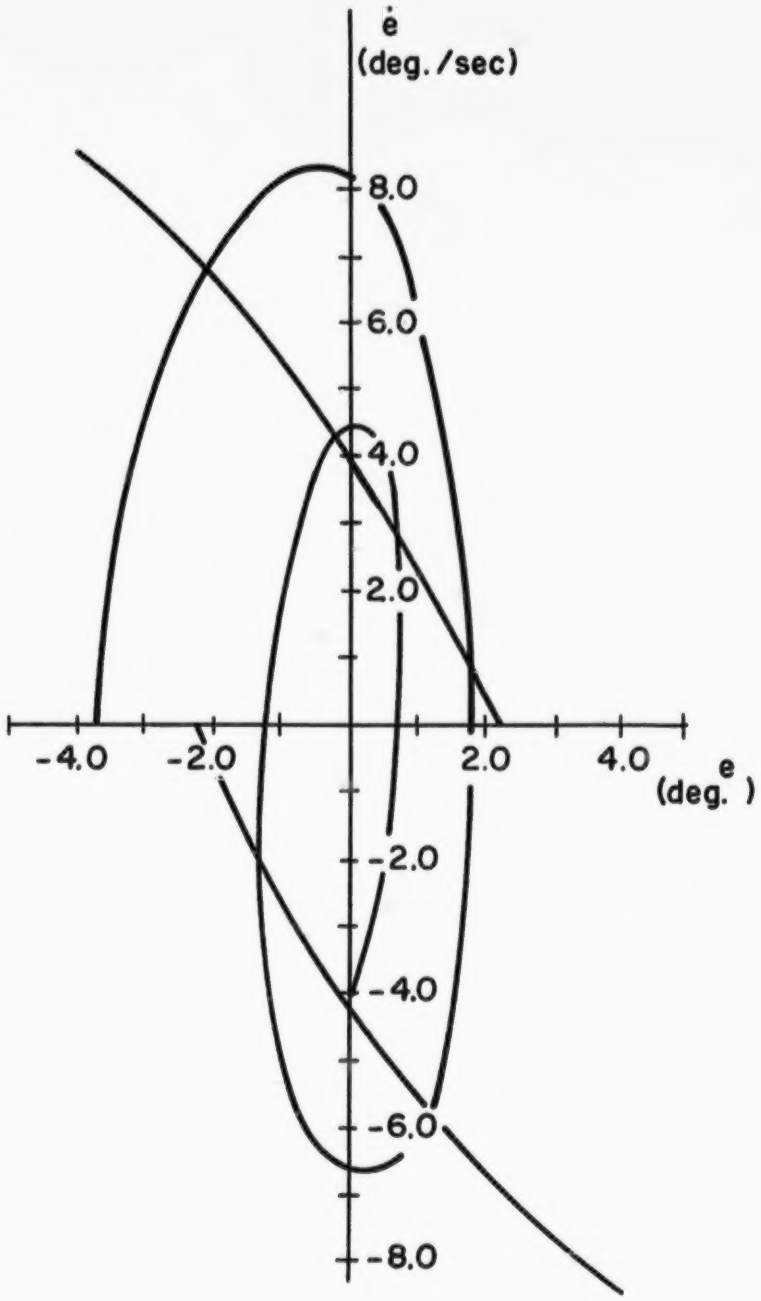

Figure 7.5. Calculated Phase Portrait and Switching Lines

equalization introduced by the human operator; the smaller the slope, the larger the phase lead. The results of this computation are given in Figure 7.6. The value of τ computed from Eq. (31) was

$$0.095 \leq \tau \leq 0.11 \qquad (32)$$

for all the conditions tested in this series.

The intended lead equalization provided by the human operator under various sensing combinations is important in its absolute magnitude as well as its relative values. For visual control, the trend is for less lead compensation with increasing ω_d (difficulty of control). On the contrary, the vestibular-tactile control produces more and more lead, as needed by the system for an increase in ω_d. For relatively easy controlled

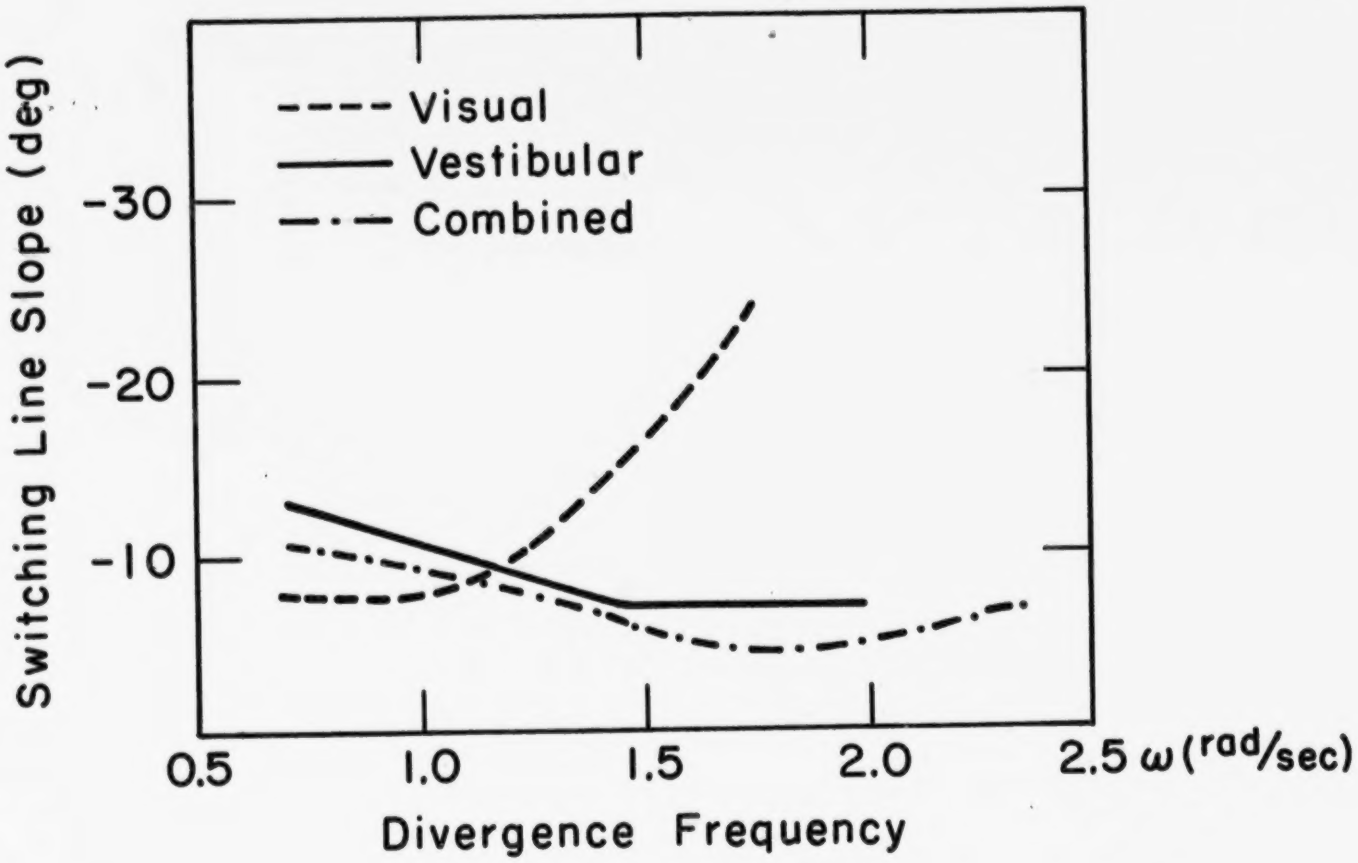

Figure 7.6. Switching Line Slope for Control of Inverted Pendulum

elements ($\omega_d < 1$) the vestibular-tactile lead term is less than that found with pure visual control. It might be expected, then, that combined visual-motion control will be the best combination of sensing capabilities both for low and high values of ω_d as is generally found in Figure 7.6.

The lead equalization, aside from its requirement for stabilization, is also an indication of the expected performance of the overall loop. If rms error is chosen as the performance criterion, the control with motion sensing should be superior to the visual one for difficult control situations and the combined control would be the best for the whole range of divergence frequencies. The results presented in Figure 7.7 closely support the lead equalization data. It is found that for every control situation, the rms error increases with divergence frequency due to the increasing difficulty of the control task. The rms errors recorded with visual control exceed by far those taken for motion tracking, when the divergence frequency is increased beyond $\omega_d = 1$. With combined sensing, the human operator maintains somewhat lower rms error than that scored with the vestibular sensors only, and is able to extend the controllable range of divergence frequency to $\omega_d = 2.25$.

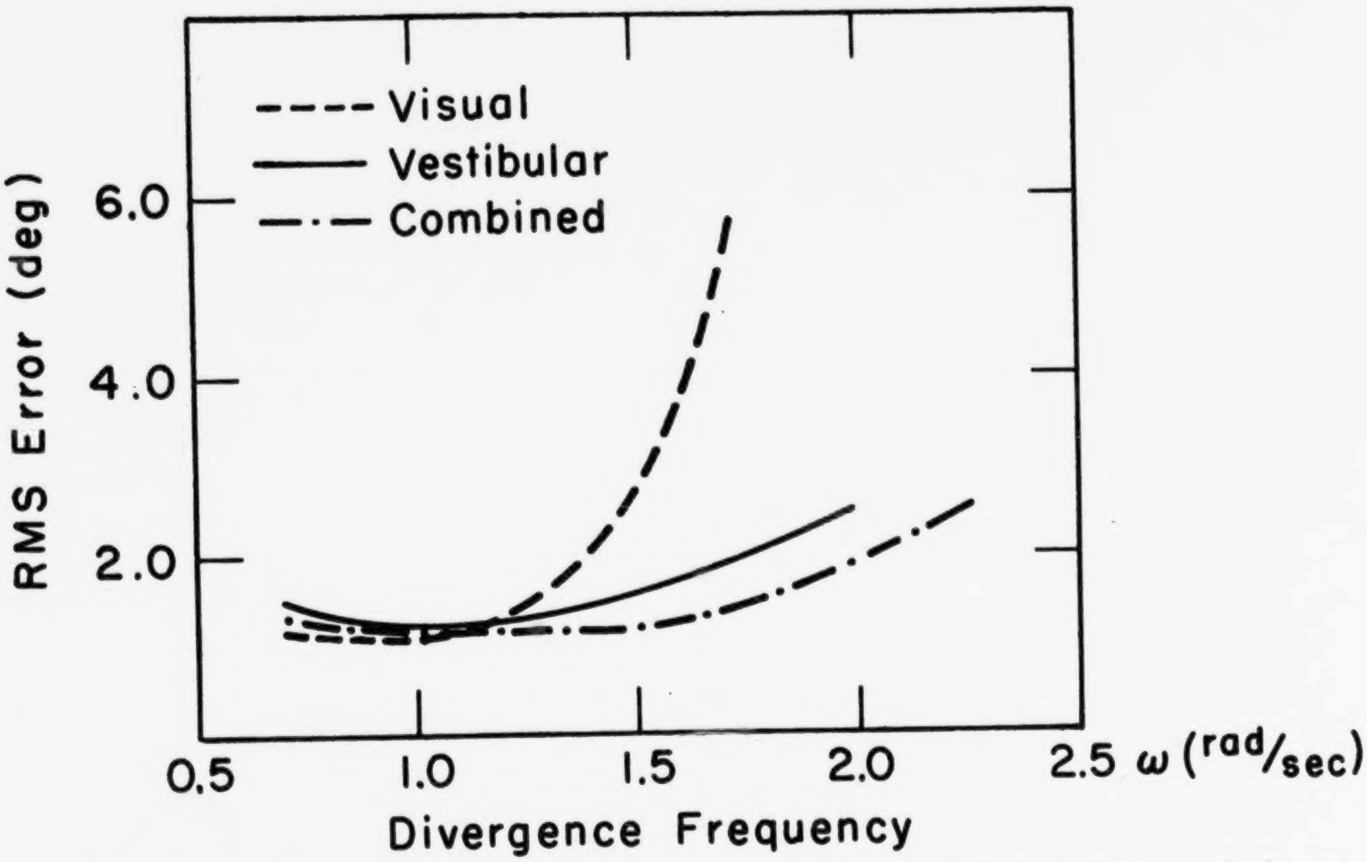

Figure 7.7. RMS Error for Control of Inverted Pendulum

The information on the human operator provided by the on-off model is useful in determining the overall loop stability and behavior. In Figure 7.2 a limit cycle of 1/4 to 1/3 cps with rather constant amplitude of about 1° is observed. The theoretical trajectory in Figure 7.5, computed for the same experimental conditions (visual tracking, $\omega_d = 2$) points to a limit cycle with parameters similar to the measured ones. The limits of control reached by the operator at high ω_d are predictable too on the phase plane. For this unstable region, large portions of the effective switching lines lie in the first and third quadrant; thus the operator is adding energy to the system contrary to the requirements.

Discussion

The series of experiments just described were initiated with the specific intention of demonstrating the contribution of man's motion sensing abilities in control of vehicle motion. The acceleration sensors of the vestibular system have been shown previously to be a channel of information with a resolution depending upon the thresholds of perception. Therefore, the lead compensation capabilities with vestibular sensing should be superior to those of the visual system in which direct sensing of velocity is a secondary function.

The experimental results support the observation about the role of the vestibular sensors in control situations where the lead compensation is essential for stable closed loop performance. The rms error, as a single scoring indicator, is also a significant description of the control utilization of the vestibular sensors by the operator. For a system with low divergence, the response is sluggish and errors often do not exceed the threshold of the human sensors. The system error for these conditions will be large for motion sensing, compared with the fine resolution capabilities of visual control. With difficult control tasks, where adequate rate information is required, the system response falls well within the frequency range of the vestibular sensors and the operator's control is improved as reflected by the values of the rms errors.

The experimental results merit some comments on fixed base versus moving base simulation. It was shown here that the visual system is inadequate for vehicle control in orientation tasks with high lead compensation requirements. These systems are highly oscillatory, they diverge fast and in general are controlled, within a region of marginal stability, to a limit cycle. Stability cannot be achieved under those conditions without adequate rate information. Consequently, control quality deteriorates rapidly whenever the human operator is deprived of his natural sensation of motion. According to the experimental results presented here, it can be stated that for missions where lead compensation is a needed control characteristic of the operator, moving base simulation will prove to be an easier task and closer to reality than fixed base simulation.

The proposed on-off model for the human operator and its analysis in the phase plane demonstrate the potential of this approach for a wide class of control situations usually referred to as limits of control of the operator. The controlled elements in these situations are generally ones for which fine minor control about the reference is either not possible or not necessary. Such systems will typically exhibit a steady state limit cycle and the performance of the closed loop is often determined by the amplitude and frequency of the terminal limit cycle. When a human operator is called upon to control such an element, his task will correspond to that of establishing a limit cycle which keeps the error within allowable bounds. It is not surprising therefore to find that the human uses a bang-bang mode in order to achieve tight control of the system while permitting some inevitable limit cycle. For the type of system discussed in these experiments, the limit cycle can result from the subject's inability to sense the true reference orientation accurately, as well as from his inability to make control corrections without any delay. The analytic approach described here indicates how the system performance may be predicted on the basis of an on-off model for the operator and its associated switching lines on the phase plane.

8. CONCLUSIONS

The object of this thesis was to investigate the control engineering characteristics of the vestibular system and the use of motion information by the human operator. This was an effort to extend the mathematical models of the operator to include the description of the role of the vestibular sensors in dynamic space orientation.

A general model of the human operator distinguished among sensors, control and compensation, and output. The thesis concentrated both on some "components" of the human and some of his system characteristics. At the sensory end, mathematical models were presented for the characteristics of the vestibular system and the eye movement control system. In control and compensation, the man's non-linear performance and his control abilities with compatible and incompatible multiple inputs were examined. Finally, in closing the loop through the dynamics of the controlled vehicle, the transfer functions of the operator with and without motion inputs were measured.

The Vestibular System

The investigation of the vestibular system was an effort to establish control descriptions of its sensors. The dynamic characteristics of the vestibular sensors, the semicircular canals and the otoliths were represented by simple mathematical models. Spatial orientation, as sensed by the vestibular system, was analyzed with respect to objective motions of the vehicle.

The semicircular canals are known to be heavily damped, angular accelerometers. Consequently, they respond as angular velocity meters over the frequency range from 0.02 cps to about 1.5 cps. The thresholds of perception of angular acceleration are $0.14°/\text{sec}^2$ for rotation about the Y_h (yaw) axis and $0.5°/\text{sec}^2$ for rotation about the X_h (roll) axis. A similar value of threshold ($0.5°/\text{sec}^2$) is presumably valid for rotation about the Z_h (pitch) axis.

The otoliths are planar linear accelerometers sensitive to the specific force applied to the skull. Statically, they measure head orientation with respect to the apparent vertical quite accurately. This sense of orientation to the vertical is modified by habituation during prolonged stay in tilted positions. Dynamically, the otoliths function as linear velocity meters for motions with frequencies within the range 0.016 cps to 0.25 cps. The threshold of perception of linear accelerations is about $0.005g$ in the plane of the otoliths.

The mathematical models for the semicircular canals and the otoliths are summarized in Figure 8.1. Each sensor model consists of a linear second order portion followed by a nonlinearity corresponding to the threshold of perception. This overall model of the vestibular system is an engineering

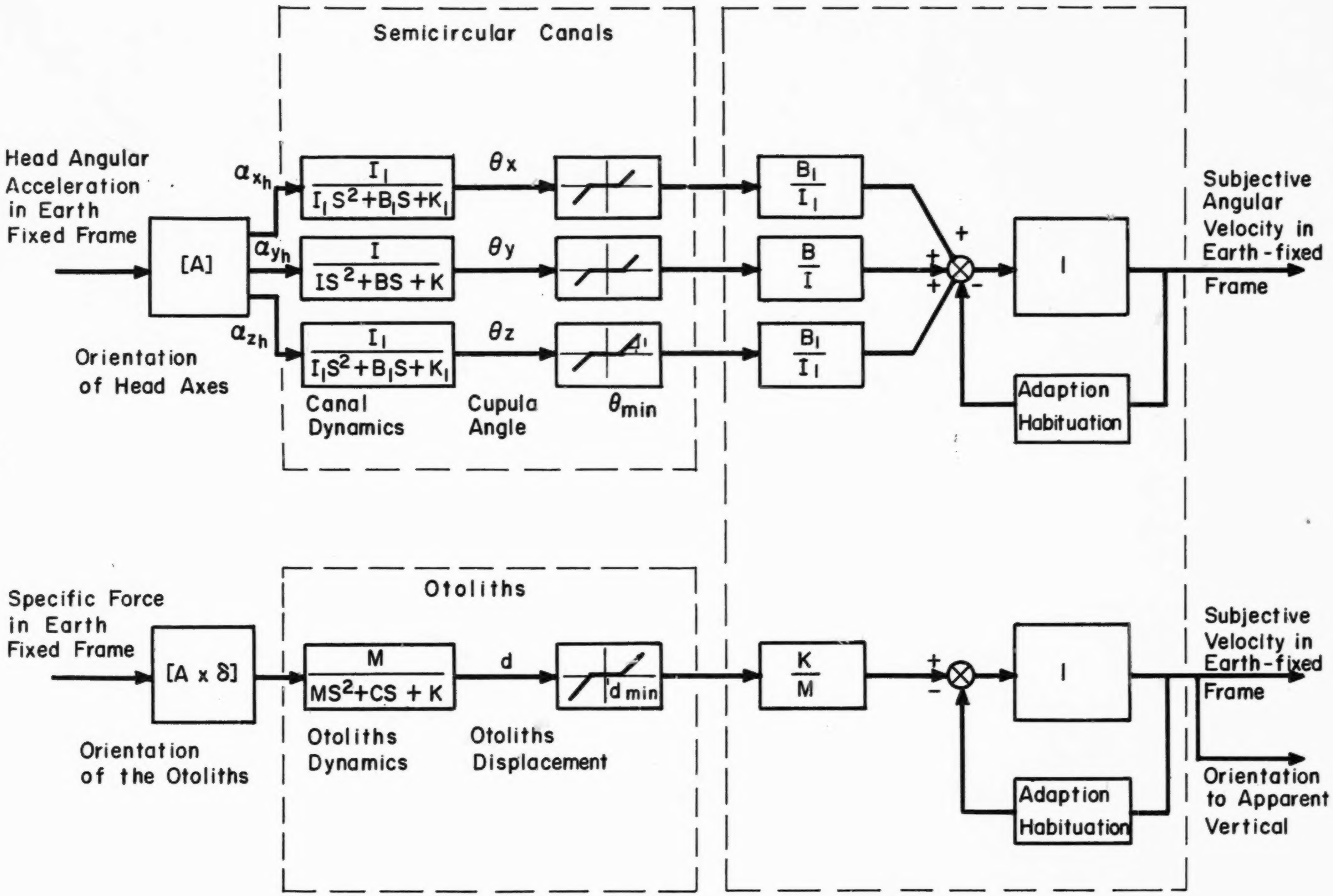
Semicircular Canals
Head Angular Acceleration in Earth Fixed Frame
[A]
Orientation of Head Axes
α_{x_h}
α_{y_h}
α_{z_h}
$\frac{I_1}{I_1 S^2 + B_1 S + K_1}$
$\frac{I}{IS^2 + BS + K}$
$\frac{I_1}{I_1 S^2 + B_1 S + K_1}$
Canal Dynamics
θx
θy
θz
Cupula Angle
θ_{min}
$\frac{B_1}{I_1}$
$\frac{B}{I}$
$\frac{B_1}{I_1}$
+
+
+
-
I
Adaption Habituation
Subjective Angular Velocity in Earth-fixed Frame
Otoliths
Specific Force in Earth Fixed Frame
[A x δ]
Orientation of the Otoliths
$\frac{M}{MS^2 + CS + K}$
Otoliths Dynamics
d
Otoliths Displacement
d min
$\frac{K}{M}$
+
-
I
Adaption Habituation
Subjective Velocity in Earth-fixed Frame
Orientation to Apparent Vertical

Figure 8.1. Block Diagram of the Vestibular System

description of the motion information perceived by the human. A "specification" summary for the vestibular sensors is given in Table 8.1.

Table 8.1

The Vestibular System

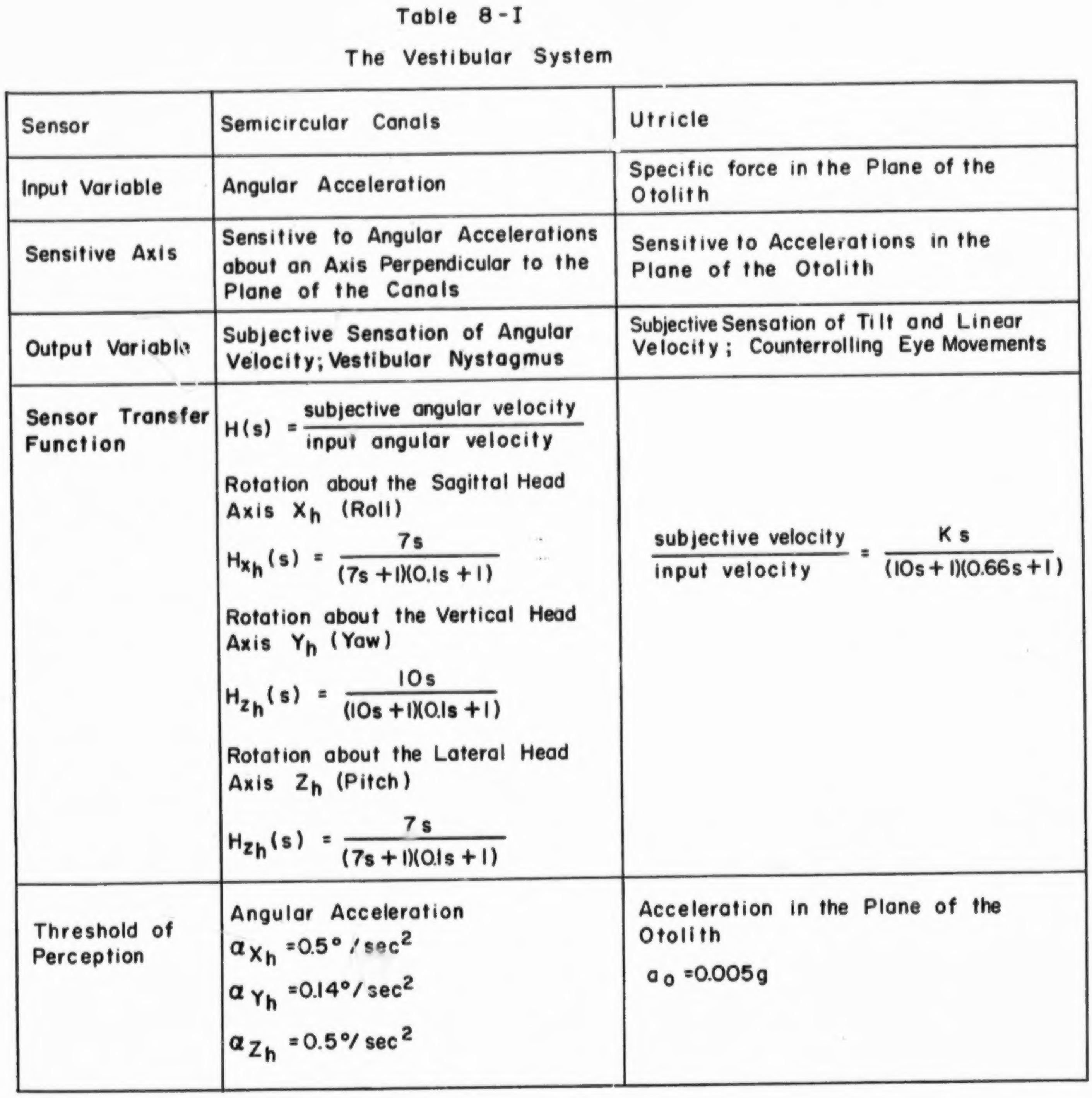

Table 8-I

The Vestibular System

Sensor	Semicircular Canals	Utricle
Input Variable	Angular Acceleration	Specific force in the Plane of the Otolith
Sensitive Axis	Sensitive to Angular Accelerations about an Axis Perpendicular to the Plane of the Canals	Sensitive to Accelerations in the Plane of the Otolith
Output Variable	Subjective Sensation of Angular Velocity; Vestibular Nystagmus	Subjective Sensation of Tilt and Linear Velocity; Counterrolling Eye Movements
Sensor Transfer Function	$H(s) = \frac{\text{subjective angular velocity}}{\text{input angular velocity}}$ Rotation about the Sagittal Head Axis X_h (Roll) $H_{x_h}(s) = \frac{7s}{(7s+1)(0.1s+1)}$ Rotation about the Vertical Head Axis Y_h (Yaw) $H_{z_h}(s) = \frac{10s}{(10s+1)(0.1s+1)}$ Rotation about the Lateral Head Axis Z_h (Pitch) $H_{z_h}(s) = \frac{7s}{(7s+1)(0.1s+1)}$	$\frac{\text{subjective velocity}}{\text{input velocity}} = \frac{Ks}{(10s+1)(0.66s+1)}$
Threshold of Perception	Angular Acceleration $\alpha_{X_h} = 0.5°/\text{sec}^2$ $\alpha_{Y_h} = 0.14°/\text{sec}^2$ $\alpha_{Z_h} = 0.5°/\text{sec}^2$	Acceleration in the Plane of the Otolith $a_o = 0.005g$

The Eye Movement Control System

Eye movements are controlled with respect to a target or reference by a multi-input control system. A program of experiments showed that the horizontal eye movement control system stabilized the eye in the presence of body and head rotations. This stabilization is within ±0.5° for frequencies up to 2 cps. Three sensory systems, the vestibular system, the neck proprioceptors and the eye itself (by visual tracking), were considered to participate in the control system. Compensatory eye movements were identified in response to stimulation of the neck proprioceptors and described by a lag-lead transfer function. The compensatory eye movements resulting from neck proprioception and those attributed to the vestibular system were found to obey superposition, indicating linearity of the control system. The control system is shown to receive rate information from the neck proprioceptors at low frequencies (up to 0.1 cps) and from the vestibular system in an overlapping intermediate range of frequencies (0.02 cps to 4.0 cps).

Control of Vehicle Orientation

The role of motion inputs to the human operator was investigated in simple vehicle orientation control systems. The control characteristics of the human in stable and unstable systems were compared under three modes of operation: visual, motion, and combined. The task was single axis compensatory orientation of a vehicle simulated by a single integration, reportedly the optimum dynamics for the human operator to control. Vehicle control to a reference orientation, by motion cues only, was found impossible with the sole exception of control of orientation to the vertical. In general, the phase lag attributed to the operator was significantly reduced when controlling with motion cues or combined visual-motion inputs, compared to control with visual input only.

The lead compensation the human can generate was also measured in a difficult compensatory task controlling an unstable system. The operator's control characteristics in this loop were distinctly nonlinear. A bang-bang model of the operator was proposed and analyzed in the phase plane and used to predict experimentally determined limit cycles.

Performance of the operator with motion cues shows significant improvement over control situations with visual input only. Motion cues extend his ability to stabilize unstable systems near the limit of controllability.

In summary, the vestibular sensors play a very significant part in providing rate information to the human operator in a closed loop system of vehicle orientation.

Appendix A

ANY-TWO-DEGREES OF ANGULAR FREEDOM MOTION SIMULATOR

The NE-2 motion simulator, shown in Figure A.1, was built by Ames Research Center, NASA. The moving cab of the simulator is mounted on two gimbals. The orientation of the gimbals and the mounting of the cab inside the gimbals may be varied to allow simultaneous rotation of the cab about any two perpendicular axes. When operated as a single axis motion simulator, the inactive gimbal is locked. Each gimbal of the simulator is driven as a DC position servomechanism by an electric amplidyne-motor set. The motion simulator was modified at the Man-Vehicle Control Laboratory to adapt it to the required angular acceleration levels for studies of the vestibular system.

The motion characteristics of the simulator in the roll-yaw mode are

Maximum rotation--yaw: ±35°
roll: ±360°

Maximum angular velocity--yaw: 2 rad/sec
roll: 8 rad/sec

Maximum angular acceleration--yaw: 10 rad/sec^2
roll: 15 rad/sec^2

Maximum angular acceleration noise--yaw: $0.1°/\text{sec}^2$
roll: $0.05°/\text{sec}^2$

The dynamics of the simulator can be approximated to a pure dead time delay, $e^{-0.1s}$ in roll and $e^{-0.15s}$ in yaw. The bandwidth of both servo loops is flat to 2 cps.

Appendix B

LINEAR MOTION SIMULATOR

The linear motion simulator, built at MIT (152), is a carriage which can be driven along a 32-ft horizontal track. The carriage has four rubber wheels running on the concrete laboratory floor. Its lateral movement is reduced by two teflon runners, which straddle a guide rail. The carriage is driven along the track with a spring-loaded continuous steel cable. The linear motion simulator is driven as a position servomechanism by a hydraulic valve energizing a hydraulic motor.

The performance parameters of the simulator are:

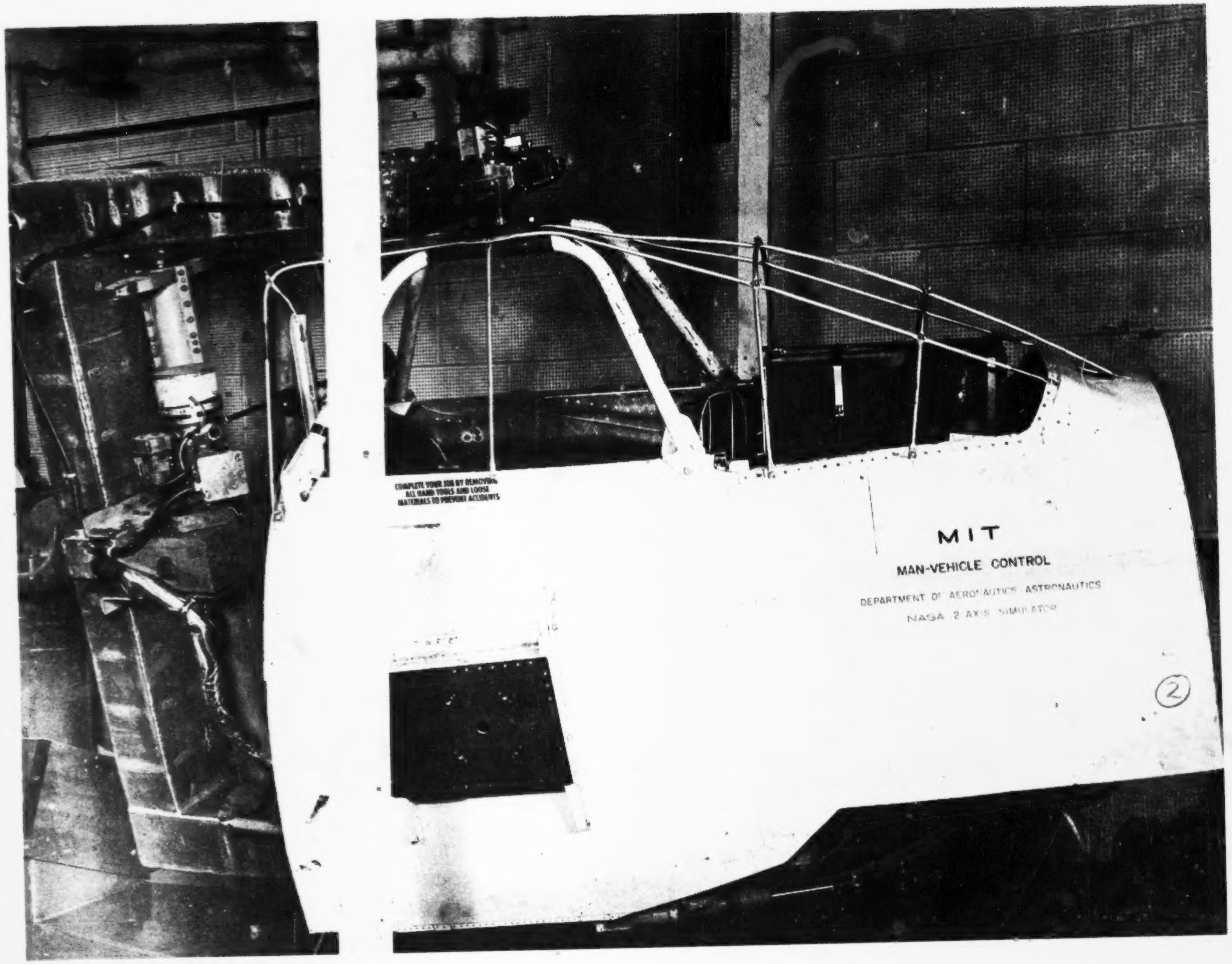
COMPLETE YOUR JOB BY REMOVING ALL HAND TOOLS AND LOOSE MATERIALS TO PREVENT ACCIDENTS
MIT
MAN-VEHICLE CONTROL
DEPARTMENT OF AERONAUTICS ASTRONAUTICS
NASA 2 AXIS SIMULATOR
②

Figure A.1. The NE-2 Motion Simulator in the Yaw-Roll Mode

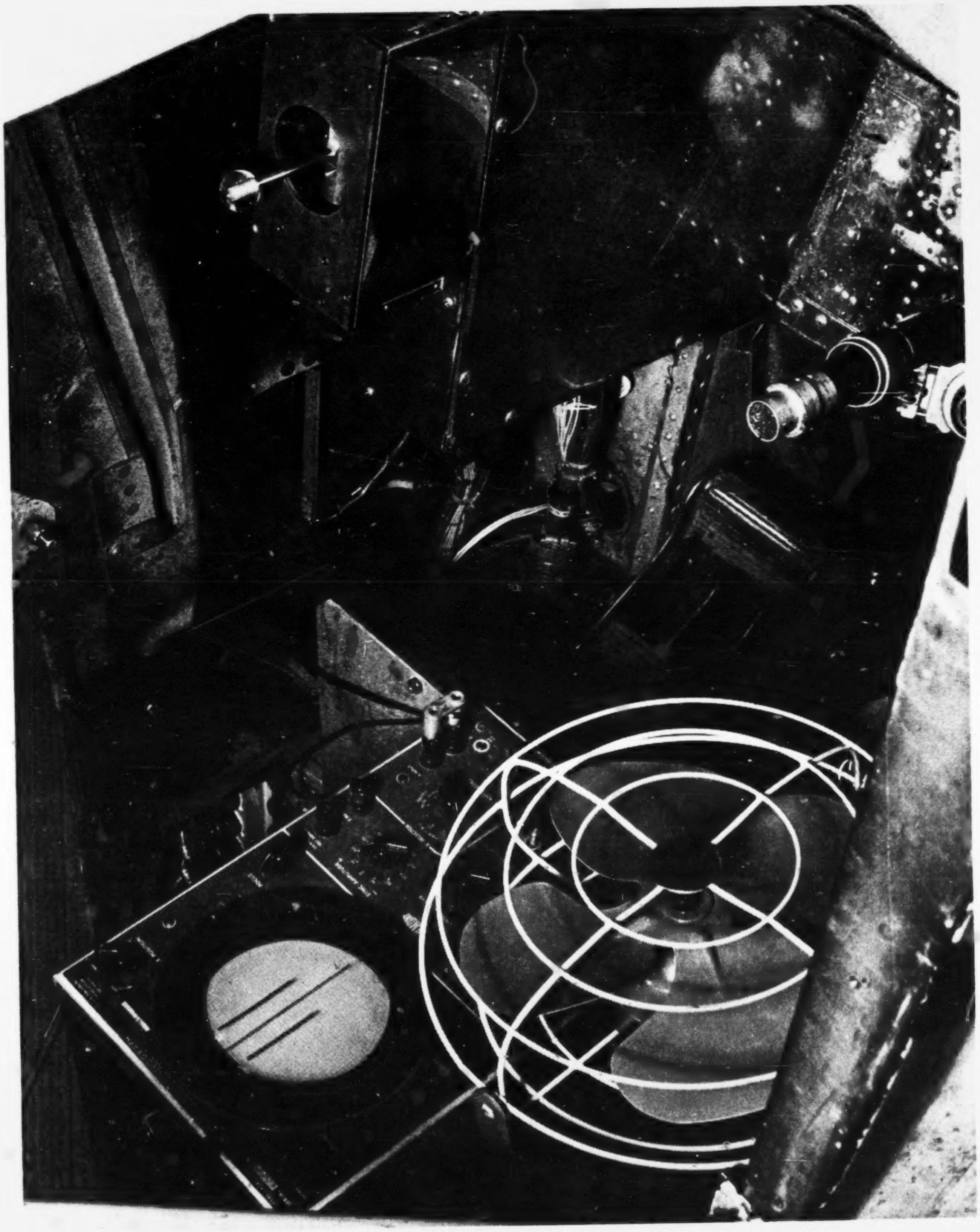

Figure A.2. The Display Scope and the Control Stick Used with the NE-2 Motion Simulator

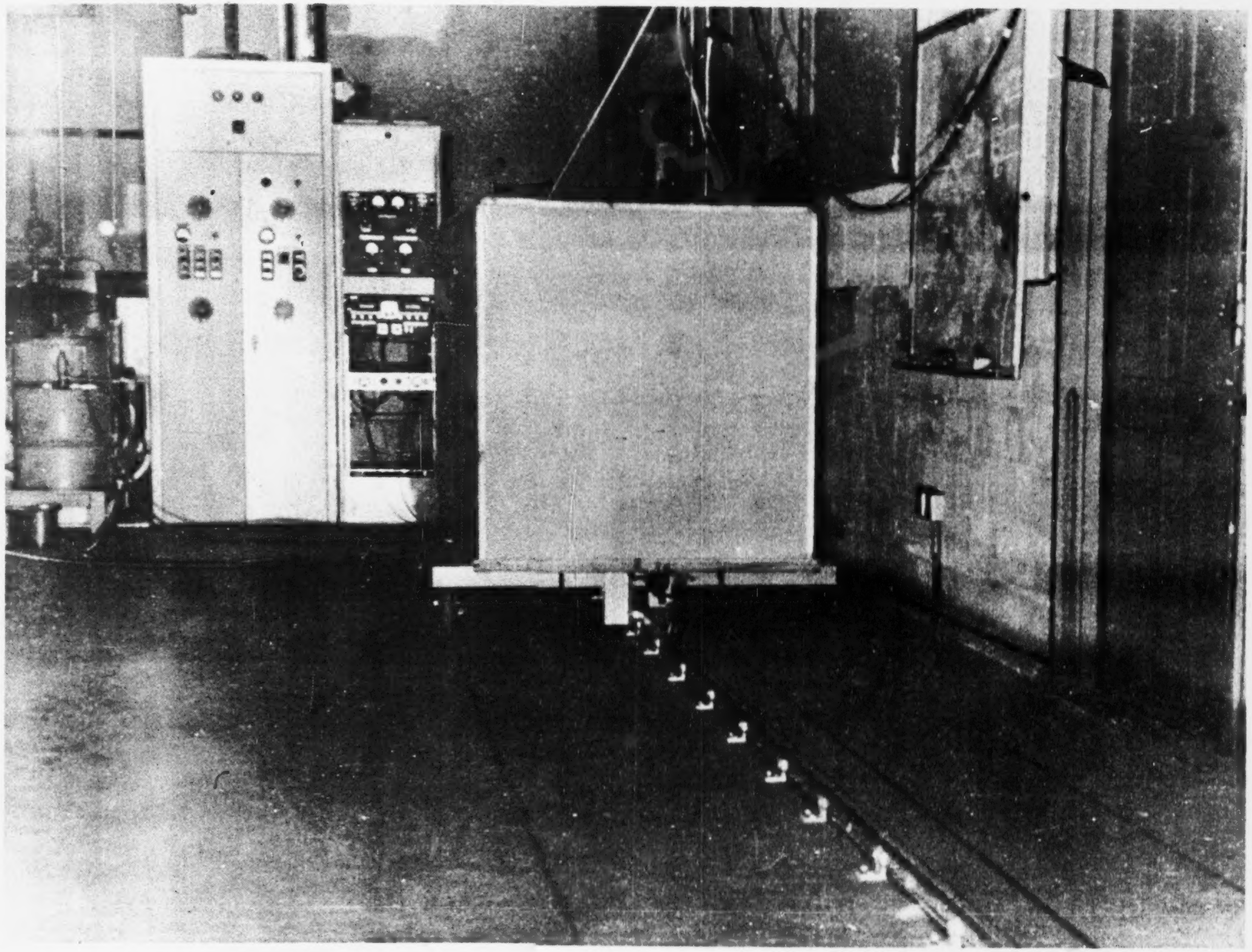

Figure B.1. The Linear Motion Simulator on Its Track

Maximum travel--32 ft

Maximum constant acceleration--$0.3g$

Minimum constant acceleration--$0.003g$ to $0.005g$

Bandwidth--DC flat to 0.9 cps

Dynamics--approximately $e^{-0.15s}$

Lateral and vertical vibrations of the carriage along the track do not exceed $0.01g$.

The carriage is covered with a lightproof cardboard structure. The subject is seated on a chair which can be adjusted from 90° sitting to supine.

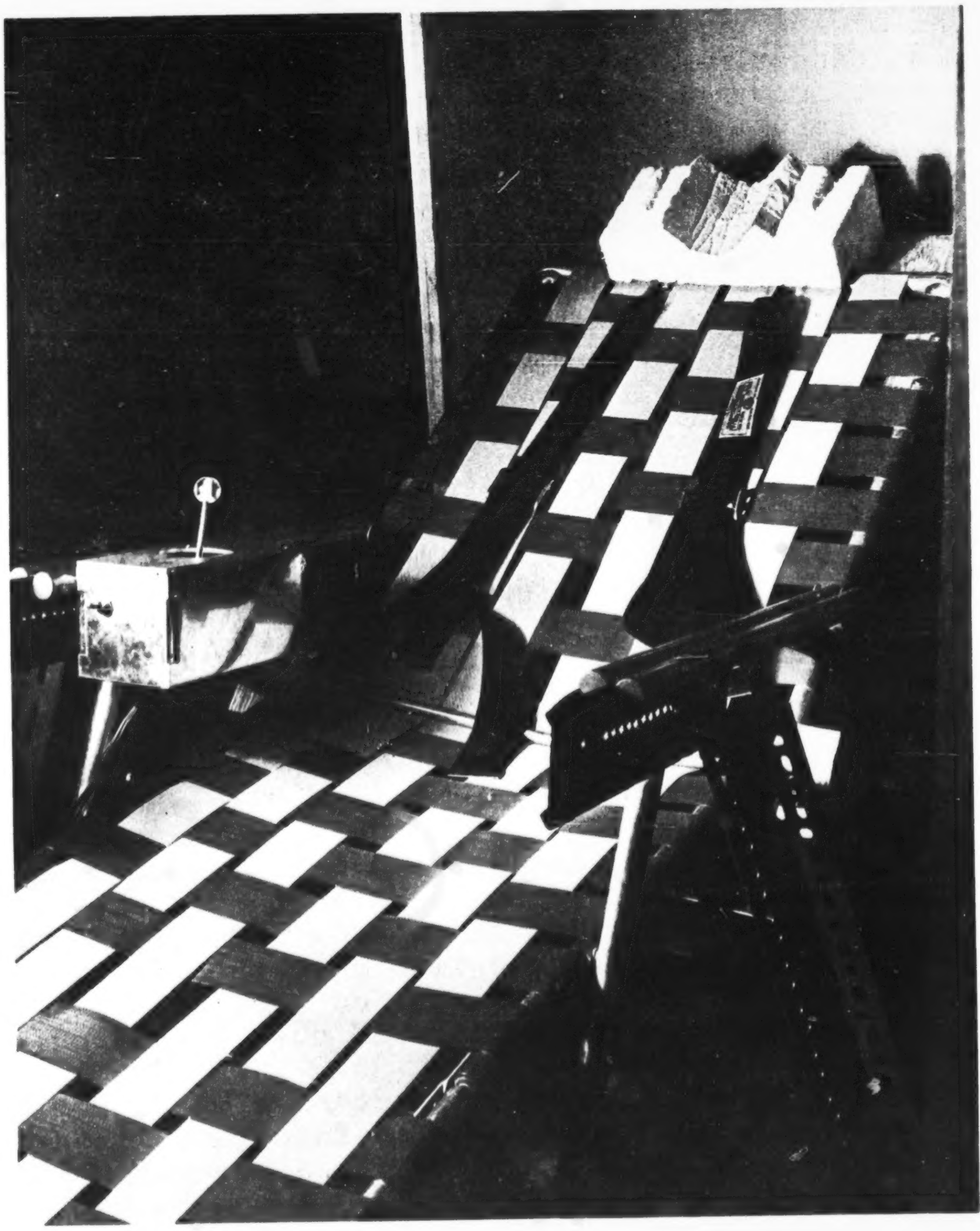

Figure B.2. The Interior of the Linear Motion Simulator

Appendix C

ANATOMY OF THE NECK—ROTATION (76)

Rotation of the head with respect to the trunk is a coordinated effort of a number of joints and muscles. The head rotates about a vertical axis on a pivot joint. The dens of the axis vertebrae are a pivot around which the atlas rotates. These are the atlanto-axial joints which form a sealed capsule containing a viscous fluid called synovia. The atlanto-axial joints are three: (*1*) the two lateral atlanto-axial joints together with the ligamentum florum in back and part of the longitudinal ligament in front, form the joint cavity which encloses the space between the atlas and the axis vertebrae; (*2*) the median atlanto-axial joint is the pivot joint between the dens of the axis and the ring in the atlas.

Simultaneous movement of all the three atlanto-axial joints must occur to allow the rotation of the atlas and the skull with it upon the axis. The angular travel of the head is limited to about 150°. The muscles which produce these movements are the Obliquus capitus inferior, the Rectus capitus posterior major and the Splenius capitus of one side, acting with the Sternocleidomastoid of the other side. Note that rotational motion of the head is induced by three muscles running along the back of the neck, counterbalanced by the Sternocleidomastoid muscle which contours the side of the neck. The nerves activating the muscles involved in rotation of the head branch from the cervical plexus, and are believed to be for proprioception.

Appendix D

MEASUREMENT OF DESCRIBING FUNCTIONS FOR THE HUMAN OPERATOR

The characteristics of the human operator in simple compensatory manual control systems can be described by a quasi-linear describing function (128). This approach is based on the notion that the operator's performance reaches stationary after learning the control task. Since the inputs to the system are in general random of "random appearing functions," the human cannot predict their time pattern. Consequently his characteristics in these manual control systems are assumed to be stationary, when measured over a limited period of operation.

The quasi-linear control characteristics of the human operator consist of (*1*) a describing function, linearly correlated with the system input; and (*2*) a remnant which is uncorrelated with the system input. This description of the operator's performance in compensatory control systems is one generally used and is analyzed extensively by McRuer and Krendel.

The most common techniques of describing and analyzing stationary signals are by correlation functions and power spectral densities. The power spectral densities which are measurable in a compensatory manual control system are the following:

$\Phi_{ii}(\omega)$ = input power spectral density

$\Phi_{cc}(\omega)$ = operator's response power spectral density

$\Phi_{ie}(\omega)$ = cross power spectral density of input and system error

$\Phi_{ic}(\omega)$ = cross power spectral density of input and operator's response

Since by definition the remnant is uncorrelated with the system input, one obtains the following equations:

$$\Phi_{ie}(\omega) = \frac{1}{1 + Y_p(j\omega)Y_c(j\omega)} \Phi_{ii}(\omega) \tag{D.1}$$

$$\Phi_{ic}(\omega) = \frac{Y_p(j\omega)}{1 + Y_p(j\omega)Y_c(j\omega)} \Phi_{ii}(\omega) \tag{D.2}$$

where $Y_p(j\omega)$ = the describing function of the human operator, and

$Y_c(j\omega)$ = controlled element transfer function.

A division of Eq. (D.2) by Eq. (D.1) will yield the describing function of the human operator as:

$$Y_p(j\omega) = \frac{\Phi_{ic}(\omega)}{\Phi_{ie}(\omega)} \tag{D.3}$$

Note the difference between the method of measuring the operator's describing function here and the standard evaluation of transfer functions in linear systems. If the human did not inject a remnant term $N_c(j\omega)$, his transfer function could be measured as:

$$Y_p(j\omega) = \frac{\Phi_{ec}(\omega)}{\Phi_{ee}(\omega)} \tag{D.4}$$

where Φ_{ee} = system error spectral density and

Φ_{ec} = cross spectral density of system error and operator's response.

However, both these spectral densities contain the effect of the remnant output. Thus, they are not valid estimates of the describing function. This difficulty is overcome by cross-correlating the signals in the system with the input, a process which eliminates the effect of the uncorrelated remnant.

From the block diagram of Figure 6.1 one obtains the following relations:

$$C(j\omega) = \frac{Y_p(j\omega)}{1 + Y_p(j\omega)Y_c(j\omega)} I(j\omega) + \frac{N_c(j\omega)}{1 + Y_p(j\omega)Y_c(j\omega)} \qquad (D.5)$$

$$\Phi_{cc}(\omega) = \left| \frac{Y_p}{1 + Y_pY_c} \right|^2 \Phi_{ii}(\omega) + \left| \frac{1}{1 + Y_pY_c} \right|^2 \Phi_{nn_c} \qquad (D.6)$$

$$\Phi_{nn}(\omega) = \left| \frac{1}{1 + Y_pY_c} \right|^2 \Phi_{nn_c}(\omega) \qquad (D.7)$$

$$\Phi_{cc}(\omega) = \left| \frac{Y_p}{1 + Y_pY_c} \right|^2 \Phi_{ii}(\omega) + \Phi_{nn}(\omega) \qquad (D.8)$$

where $\Phi_{nn_c}(\omega)$ = remnant power spectral density at the operator's output

$\Phi_{nn}(\omega)$ = remnant power spectral density expressed as a closed loop quantity.

The relation $H = Y_p/1 + Y_pY_c$ is the closed loop describing function of the operator measured from system input to operator's output. Consequently,

$$\Phi_{cc}(\omega) = | H |^2 \Phi_{ii} + \Phi_{nn} \qquad (D.9)$$

Equation (D.9) indicates that the total operator power spectra contains two portions: (*1*) a part correlated with the system input, and (*2*) a closed loop noise power injected in the system. The ratio of the spectral density correlated with the system input to the total operator spectra is the square of the linear correlation,

$$ {}^{2} = \frac{| \; H \; |^{2} \; \Phi_{ii}(\omega)}{\Phi_{cc}(\omega)} = 1 - \frac{\Phi_{nn}(\omega)}{\Phi_{cc}(\omega)} \qquad \text{(D.10)} $$

Since

$$ H = \frac{\Phi_{ic}(\omega)}{\Phi_{ii}(\omega)} \qquad \text{(D.11)} $$

$$ {}^{2} = \frac{| \; \Phi_{ic}(\omega) \; |^{2}}{\Phi_{ii}(\omega) \; \Phi_{cc}(\omega)} \qquad \text{(D.12)} $$

The describing function of the human operator can be determined from Eq. (D.3). The correlation coefficient ^{2} is evaluated from Eq. (D.12). A value of ^{2} near unity implies that the operator's performance is well accounted for by his describing function.

The most frequently used method of measuring describing functions is by digital computation. In this method, an analog record T seconds long is sampled every ΔT seconds. The correlation function and the power spectral density are determined from the total $M = T/\Delta T$ points. The correlation function is evaluated for m lags of ΔT. Several considerations are involved in the use of this method.

1. The sampled data can have no spectral power at frequencies above ω_{high} where:

$$ \omega_{\text{high}} = \frac{\pi}{\Delta T} \qquad \text{(D.13)} $$

Consequently ω_{high} has to be a frequency above which the continuous signal does not have appreciable power.

2. Since the spectral density is evaluated at m points equally spaced in the range of frequencies 0 - ω_{high}, the frequency resolution of the digitally computed, power spectral density is:

$$ \Delta\omega \quad \frac{\pi}{m\Delta T} \qquad \text{(D.14)} $$

3. The probable error of the computed spectral density is (20):

$$\varepsilon = \frac{\sqrt{|\Phi(\omega)_{\text{measured}} - \Phi(\omega)|^2}}{\Phi(\omega)} = \frac{m}{M} \qquad \text{(D.15)}$$

This error is reduced when the spectral densities are averaged for N independent computations:

$$\varepsilon = \frac{m}{NM} \qquad \text{(D.16)}$$

Equation (D.15) indicates that m should be a small fraction of M; in general, use $m = 0.1M$.

A program, written by the staff of Health Sciences Computing Facility, UCLA and made available to the author by Ames Research Center, NASA, was used for the experimental series reported in section six. This program for autocovarience and power spectral analysis was modified to compute the describing function of the human operator according to Eq. (D.3). The following parameters were used for the computation procedure:

$T = 90$ sec

$T = 0.2$ sec

$M = 450$ points, $\varepsilon = \frac{m}{NM} = 0.1$

$m = 45$ lags

$N = 10$

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EDITOR'S NOTE

Those readers who are familiar with the Proceedings of the International Congress on Technology and Blindness (published by the American Foundation for the Blind in 1963) will know that Volume IV (Catalog Appendix), issued in paperback form, was to be updated and reprinted as a hard-cover volume some time in the future by our British colleagues. For a variety of very good reasons, this has proved to be (as we might have suspected) a good deal more difficult a job than had first been anticipated. Meanwhile, there is no adequate vehicle in our community of interest for conveying news of development of instrumentation.

In *Research Bulletin 16*, we initiated the Research Bulletin Supplement (but, we were embarrassed to discover, without this explanatory note). Supplement pages are perforated along one edge so that they may be torn out and filed according to your own system and preference. The format of the Supplement resembles that of the listings in Volume IV of the Proceedings, except that we have added photographic information when available.

The success of this innovation depends on your reaction and on your contribution to the Supplement. Comments negative and positive are welcomed and solicited.

Your attention is also directed to the Publications of Note. Documents noted belong, as we believe the Bulletin does, in a core reference for sensory research related to sensory impairment.

The third innovation in this issue is the Proposal for Research section, described in the accompanying note.

5

PROPOSALS FOR RESEARCH ON BLINDNESS AND SEVERE VISUAL IMPAIRMENT: THE SOCIAL SCIENCES

Editor's Note:

IRIS has received, from time to time, requests that it disseminate proposals for research. Some researchers feel that such suggestions may help stimulate the thinking of themselves and their colleagues. Others feel that by presenting such a listing to students we may hope to engage their interest, either in applied research or in basic research which has potential applications to what, lately, we have been calling "practice theory."

The following suggestions developed from a free-ranging discussion among Eric Josephson of the Columbia School of Public Health, Robert A. Scott of Princeton University, Hyman Goldstein of the Children's Bureau of HEW, Milton D. Graham of the AFB, and Leslie L. Clark of IRIS/AFB. The focus was on social science research. Additions, suggestions, and criticisms are solicited from our readers; we also propose that you send us suggestions for research allied to the physical sciences for inclusion in a future issue of the Bulletin.

1. The early identification of genius
2. The early retardation of talent
3. The Blindness Register and the question of the "hidden blind"
4. A cross-cultural study of blindness
5. A cross-subcultural study of blindness
6. The social problem of blindness as determined by the social response to blindness
7. The relationship of "retardation" to "blindness"
8. The relevancies of basic social and physical science theories for a practice theory of blindness
9. The differential consequences of differing definitions of blindness
10. Stress, anxiety, and tolerance for ambiguity and frustration and the question of "adjustment"

Some additional thesis topics, culled from the report on the 1966 International Conference on Social Work, include:

1. The consequences of dissolution of family life due to migration and/or urbanization

2. Anticipatory studies or predictive studies of the life styles which the young can expect in the future; and the institutions and methods best suited to prepare them for that future

3. Study of the specific social problems facing children, and an analysis of the causes and probable effects

4. The problems in integrating the programs available nationally and internationally to benefit youth

5. Studies of the waste of natural talent: drop-outs and stagnation

PUBLICATIONS OF NOTE

Binocular Visual Acuity of Adults, by Region and Selected Demographic Characteristics, United States, 1960-1962. National Center for Health Statistics, Series 11, Number 25, Public Health Service Publication No. 1000, June, 1967.

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Fraser, J. R., and Friedmann, A. I. *The Causes of Blindness in Childhood.* Baltimore: Johns Hopkins Press, 1968. 245 pp.

The reader's attention is called to the following two references to the Sixth Technical Session on Reading Machines for the Blind, held in Washington, D.C., in January, 1966.

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Freiberger, Howard, and Murphy, E. F. "Reading Machines for the Blind," *Science*, 152(3722):679-80 (April 29, 1966).

The most detailed public record is contained in a summary prepared in February of 1968, and reproduced in very limited supply by the Veterans Administration for distribution to several archives. If a reader wants a copy of this more comprehensive summary, however, we shall be glad to provide a photocopy of the document, if he will send us a written request for it. The quality of the printing is not high, but it is readable. And it is more complete than other published versions of the proceedings of the meeting.

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Lauer, Harvey L. "The Visotoner," *The New Beacon*, LII(612): 98-100.

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Rice, Charles. "Human Echo Perception," *Science*, 155(3763):656-64 (February 10, 1967).

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Proceedings of the Louisville Conference on Time-Compressed Speech. (October 19-21, 1966.) Louisville, Ky.: Center for Rate Controlled Recordings, University of Louisville, 1966. 168 pp. $2.50.

ITEM: Proceedings of the Louisville Conference on Time Compressed Speech

PRICE: $2.50 per copy

MAKE CHECK PAYABLE TO: University of Louisville

ORDERING ADDRESS:

Dr. Emerson Foulke, Director
Center for Rate Controlled Recordings
University of Louisville,
Louisville, Kentucky 40208

MAIL TO: (Please include zip code)

(Name) ______________________________

(Address) ______________________________

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QUANTITY DESIRED:

METHOD OF PAYMENT: Check Cash Money order

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RESEARCH BULLETIN SUPPLEMENT

Name: Audible Carpenter's Level Study
Source: American Foundation for the Blind
Availability: In experimental stage

A study of designs for a new level has been initiated.

Name: Audible Multimeter
Source: American Foundation for the Blind
Availability: On request

The Audible Multimeter is a greatly improved Auditory Circuit Analyzer which allows blind users to make a variety of electronic and electrical measurements. Accuracy matches that of devices used by sighted persons. A set of instructions has also been written for the device.

Name: Harmonic Speech Compressor
Source: American Foundation for the Blind
Availability: Experimental prototype

Work continues on the construction of this analyzer. The remanufactured band-pass filters have been received from the supplier.

Name: Improved Tellatouch
Source: American Foundation for the Blind
Availability: Production prototype

Tooling has been completed for the improved Tellatouch deaf-blind communicator. A production run of 25 special keyboards was started with the improved device.

Name: Solid State Audio Amplifier
Source: American Foundation for the Blind
Availability: Experimental prototype

Work continues on a solid state amplifier designed for use with a proposed talking book disc reproducer.

Name: Study of Low Speed Tape Cassettes
Source: American Foundation for the Blind
Availability: In experimental stage

A study of low speed tape cassettes has been initiated.

Name: Study of Optical Probes
Source: American Foundation for the Blind
Availability: In experimental stage

A study has been initiated of optical probes made thus far, with the hope that the present designs can be improved upon. So far, a survey of previously available designs has been completed. Further tests are under way.

Name: Study of Saw Guides
Source: American Foundation for the Blind
Availability: In experimental stage

A study has been initiated of saw guides, so that drawings of these can be supplied on request.

Name: Tactile Speech Indicator
Source: American Foundation for the Blind
Availability: Preproduction prototype

A small serial production of this device for deaf-blind telephone communication was completed; these will be used at a training workshop.

Name: Tactile Slide Rule
Source: American Foundation for the Blind
Availability: Preprocution prototype

A study is now nearing completion of improvements to be made on the tactile slide rule.

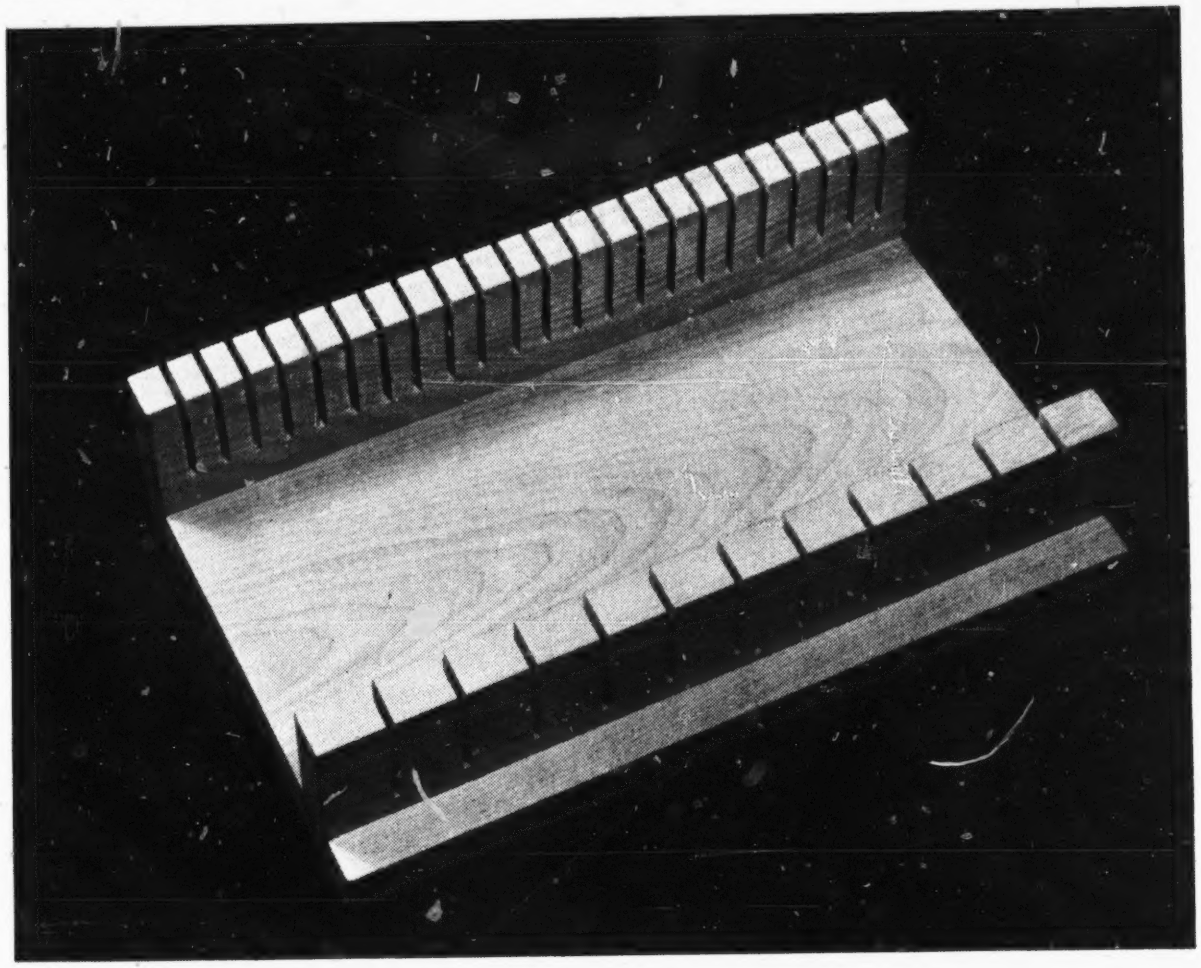
Name: Television Audio Tuner Study
Source: American Foundation for the Blind
Availability: In experimental stage

An examination of the tuners available for recovering the audio content of television transmissions, with the video content, has been initiated. One commercial receiver has been selected for close examination.

Name: Closed circuit TV system for the visually handicapped
Source: The Rand Corporation, Santa Monica, California
Availability: Experimental prototype

The prototype system uses a TV monitor resting on a shelf, a TV camera with an electrically operated servo-mechanism for moving it about, and a working surface to support reading and writing materials. The total cost of the components (commercially available units) is less than $1000. The system is thought to be of potential value to any visually impaired person who has difficulty reading and writing even with the aid of glasses, but who could carry on these operations if he had the use of a visual aid that increased magnification, brightness, or contrast, or some combination of these.

Name: Berry-Burcher Cutting Board
Source: R. Berry, State Department of Social Welfare,
2516 West Sixth Street, Topeka, Kansas
Availability: Upon request
Price: $3.00



A cutting board 12 inches by 7-1/4 inches by 3/4 inch thick is dadoed along one side for insertion of an upright wooden "comb" which serves as a cutting guide for blind or sighted persons.

Name: Combination Horn and Flashlight
Source: M. M. Meyers, 2918 Clinton Street, Fort Worth,
Texas 76106; U.S. Patent No. 2, 893, 344
Availability: Experimental prototype

The battery-operated flashlight incorporates a chamber around the battery chamber for the passage of air from a bulb-operated air pump which will actuate a reed to produce a honk. The sound is designed to alert pedestrians to the need for help by a blind traveler, and the flashlight is designed to provide illumination to those visually impaired persons with some useful vision.

Name: Cooking utensil for visually impaired users
Source: U.S. Patent No. 3,405,678, assigned to Telecommunications Research Associates (Richard E. Frenkel and Herbert M. Frenkel, New York)
Availability: Preproduction prototype

The production version of this aid will have a handle which can be used with a number of pots and pans. The handle has a set of crossbars in a ladder arrangement. The user starts from the cold end and feels the crossbars as he progresses down the ladder to assess the temperature of the contents of the pot. The handle can be covered with plastic except for buttons on the crossbars. The inventors claim that the device should be as useful as a thermometer to a blind user who might otherwise burn himself by touching a hot pot cover to discover how hot the food within the pot has become.

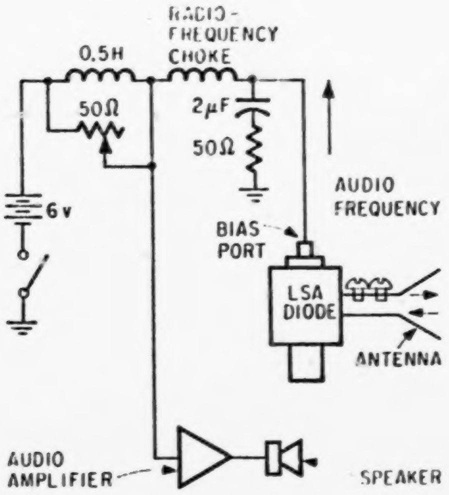
Name: Fieldgate Reading Machine
Source: Ivan O. Fieldgate, Potter Instrument Company, Plainview, Long Island, New York
Availability: Experimental prototype

This device, awarded U.S. Patent No. 3,395,247 during July, 1968, uses a recorded analogue of the braille cell to generate a tactile display. Braille characters are represented by the sound code on magnetic sound recording tape. A translator causes flat-topped pins to be raised through holes in a board for tactile sensing. The reading desk has one fingerboard on which a line at a time of braille can be read. A second fingerboard shows the source of the material, as do pages in a book. The reader can regulate the movement of the tape with a lever to suit his individual reading speed.

Name: Nonslip coated goods
Source: Dycem, Ltd., Adlams Works, Justice Road, Fishponds, Bristol, England.
Availability: From supplier
Prices: Pads 4/1d/ 2/10d
Limpet Cloth 2/6d sq ft
Trays 35/6d
Hangers 4/11d

A nonslip coating of plastic has been applied to a wide variety of goods including pads (rectangular, round), trays with or without handles, and coat and dress hangers. The articles are currently in use in occupational therapy centers in the United Kingdom.

Name: Portable inexpensive radar mobility aid
Source: Bell Telephone Laboratories (1968)
Availability: Experimental prototype

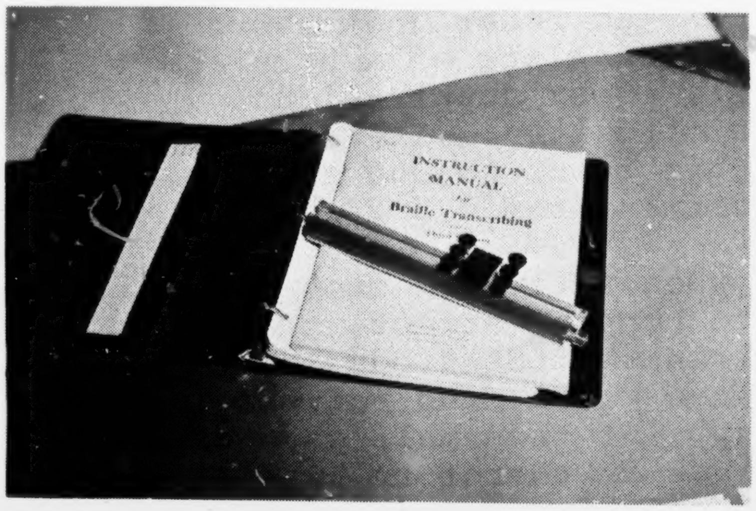


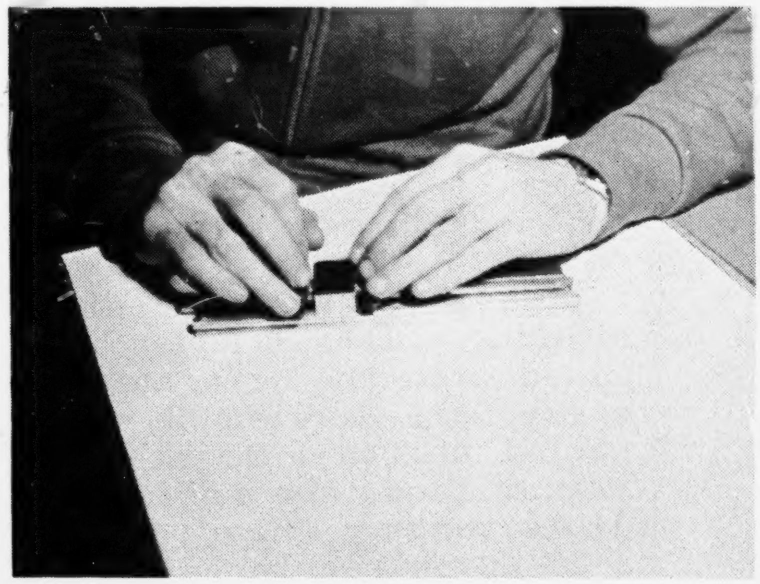
In a project to develop a prototype space charge accumulation device (LSA), J. Copeland and R. Spiwak built a five-pound, battery-operated radar unit about the size of a shoebox. The unit consists of a horn antenna, transistorized amplifier, power supply, loudspeaker, and the diode and its circuitry. It beams a 4 mw, 70 GHz (4mm) signal at objects up to 300 ft away, and detects movements of velocities from 0.5 ft/sec to 40 mph.

The transmitted signal, when reflected from an object, shifts frequency due to Doppler effect, then is mixed with the original signal in the LSA diode. For every half wavelength of distance moved, the reflected signal shifts 1 Hz in frequency. At the small wavelengths transmitted, the reflected signal is therefore in the audible range. Only 4 v and a few hundred ma is required; a 25 dB gain antenna is required to transmit a beam width of about 8 deg. Parts required are off-the-shelf, and the circuitry is extremely simple.

Bell Laboratories does not plan to develop this device further as a mobility aid.

Name: Science for the Blind Meter Reader
Source: Science for the Blind, Inc., 221 Rock Hill Road,
Bala Cynwyd, Pennsylvania 19004
Availability: From supplier
Price: $40.00



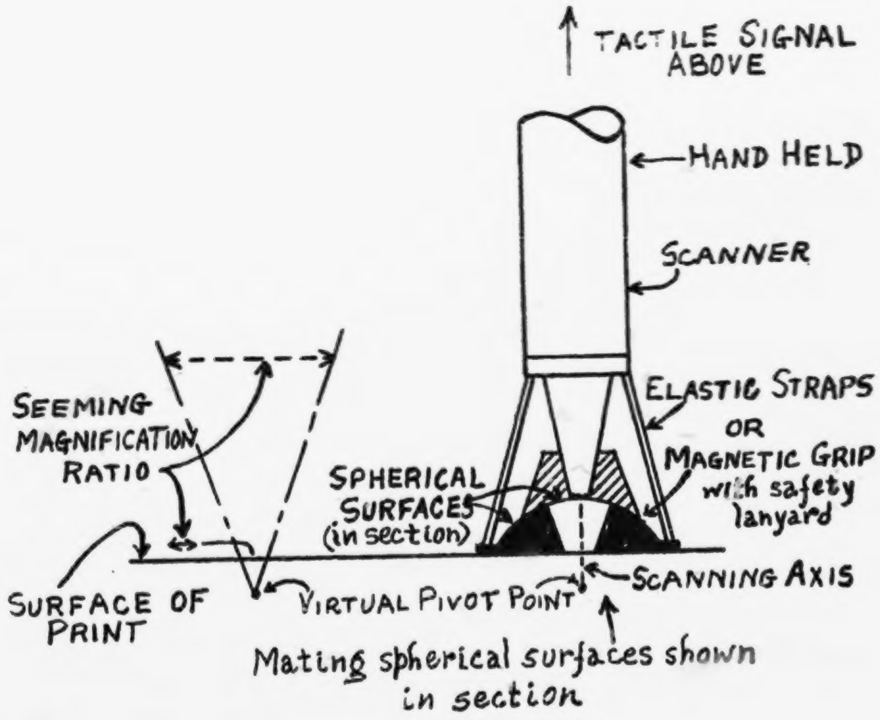


The Science for the Blind meter reader consists of a small metal box with sloping panel, on which is located a braille scale with knob and pointer. The meter reader may be connected across the terminals of any visual meter movement to allow readings to be taken by correlating an auditory signal with the braille scale.

The sensitivity of the reader is approximately 150 mv full scale; it works on dc instruments only, but may be adapted for use with ac instruments by using a diode/

capacitor rectifier unit and a voltage divider that has a known ratio and produces less than 150 mv across the meter reader. The instrument is intended primarily for connection to the meter movement of other measuring instruments.

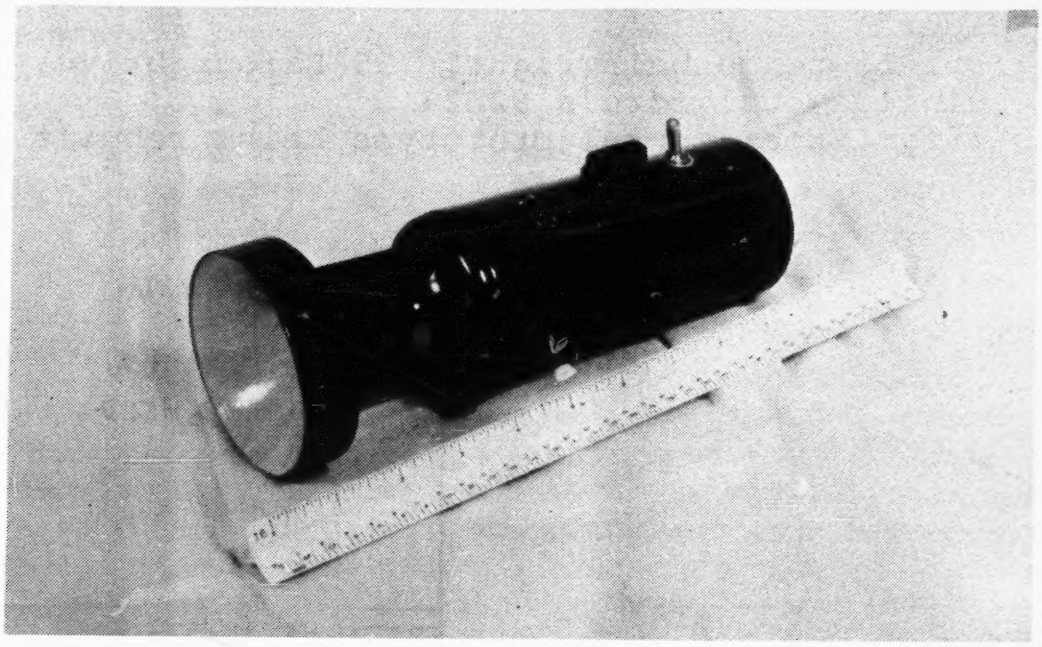
Name: Single channel optical to tactile aid--"Blind Reader"
Source: Dr. Lawrence Wainwright, 795 Balour Drive, Encinitas, California 92024
Availability: Experimental prototype being rebuilt


TACTILE SIGNAL ABOVE
HAND HELD
SCANNER
ELASTIC STRAPS OR MAGNETIC GRIP with safety lanyard
SEEMING MAGNIFICATION RATIO
SPHERICAL SURFACES (in section)
SURFACE OF PRINT
VIRTUAL PIVOT POINT
SCANNING AXIS
Mating spherical surfaces shown in section

This device "looks at" a single point. A spot on the printed page surface is illuminated by a small light source and lens system; it is also viewed by a photocell with an amplified output. Output to the user is a tactile signal indicating light detection or no light detection. The device is held in the hand with the axis vertical, and the index finger tip resting on a rod whose movement is actuated by a solenoid and amplifier within the device: the rod pushes up against the finger tip when there is no light detected, and drops down when there is light. Thus the effect in "reading" ink print characters and figures is as though the hand held a stylus and used it to feel raised letters and figures.

The American Foundation for the Blind seeks the reaction of researchers on the device design, the human engineering of the device, and the psychological assumptions involved in the design.

Name: Sondol
Source: Listening, Inc. (6 Garden Street, Arlington, Massachusetts)
Availability: Commercially available
Price: $50.00



This device is an echolocator that utilizes some of the principles developed in the construction of the man to dolphin translator in a research team headed (until his death) by Dr. Dwight W. Batteau.

In hand-held use the device is directed toward a target or obstacle. When the pulse repetition rate is adjusted so that the returning echo reaches the user's ear about halfway between the outgoing pulses, the target itself appears to emit sound. Blind persons who have used the device appear to be able to make fine discriminations among target materials and shapes after one or two hour's practice.

The device is available in narrow beam or wide beam models, emits sharp clicks with a rise time of 50 microseconds, has a repetition rate variable between 1/2 to 100 pulses per second, and has a peak output of about 10 watts. Modified housings are available on special order.

SVCR

New Listings

Name: Acoustic beacon
Source: SVCR, Bromma 3, Sweden
Availability: Production prototype in test phase

This device emits sound intermittently, thus serving the function of a beacon in orienting a visually impaired or blind person in a desired direction or course.

Name: High voltage probe
Source: SVCR, Bromma 3, Sweden
Availability: In series production

This probe detects high voltages and emits an audible signal when they are present.

Name: Survey of sensory aids needs
Source: SVEN/SVCR, Bromma 3, Sweden

This survey will attempt to explore the needs of several impaired and handicapped groups for a variety of sensory and other instrumentation meant to alleviate deficits in function and performance. The first phase of analysis of the needs of visually impaired persons is completed; the results are now being used in project planning to meet those needs. A study of the needs of arm amputees is now under way.

Name: Tape recorder control
Source: SVCR, Bromma 3, Sweden
Availability: Experimental prototype in test phase

This device will allow the operation of the controls of a tape recorder with a puff of air from the mouth or by easily operated pushbuttons.

Revised SVCR Listings

Name: Communication apparatus for the deaf-blind
Source: SVCR, Bromma 3, Sweden
Availability: Work has been suspended temporarily.

Radio-transmission of different signals to the deaf-blind in tactile form.

Name: Doorbell with tactile receiving device for the deaf-blind
Source: SVCR, Bromma 3, Sweden
Availability: Production prototype in preparation

Name: Electronic thermometer for the visually handicapped
Source: SVCR, Bromma 3, Sweden
Availability: Production prototype now under test

A thermistor is the temperature-sensitive device; and an audible output is counterbalanced to zero by a potentiometer at the correct temperature. Tactile display by identification of position of potentiometer.

Name: End position indicator for braille for the deaf-blind
Source: SVCR, Bromma 3, Sweden
Availability: Now in serial production

Name: Football for the visually handicapped
Source: SVCR, Bromma 3, Sweden
Availability: Tests of laboratory prototype completed

Football with acoustic signal for use by blind or partially blind.

Name: Guiding thread for the blind
Source: SVCR, Bromma 3, Sweden
Availability: A new prototype, with acoustic sensor, now in preparation in laboratory prototype

Magnetic thread, laid down at traffic crossings, alongside pavements, railway platforms, etc. Magnetic field is picked up by a vibrator built into the ferrule of a stick, through which it is communicated to a tactile transmitter at the handle.

Name: Recorded measurement to speech output translator
Source: SVCR, Bromma 3, Sweden
Availability: Production prototype now in preparation

Apparatus for conversion of recorded measurements into audible form, to enable the visually handicapped to perform certain kinds of work.

Name: Recording indicator for tape recorder
Source: SVCR, Bromma 3, Sweden
Availability: Production prototype now under test

Device for tactile determination of recording level.

Name: Tactile sensor
Source: SVCR, Bromma 3, Sweden
Availability: Laboratory prototype now under test

Tactile display for the blind or deaf. Two variants as displayed.

Name: Telephone amplifier
Source: SVCR, Bromma 3, Sweden
Availability: Tests of first prototype completed. A new laboratory prototype is being completed.

Small portable amplifier for application to telephone receivers; for use by persons with defective hearing.

Name: Writing aid for the visually handicapped
Source: SVCR, Bromma 3, Sweden
Availability: Work has been suspended temporarily

Draft board with ruler and set square marked with braille signs, together with special ratchet in holder, to make impressions legible from the top surface.